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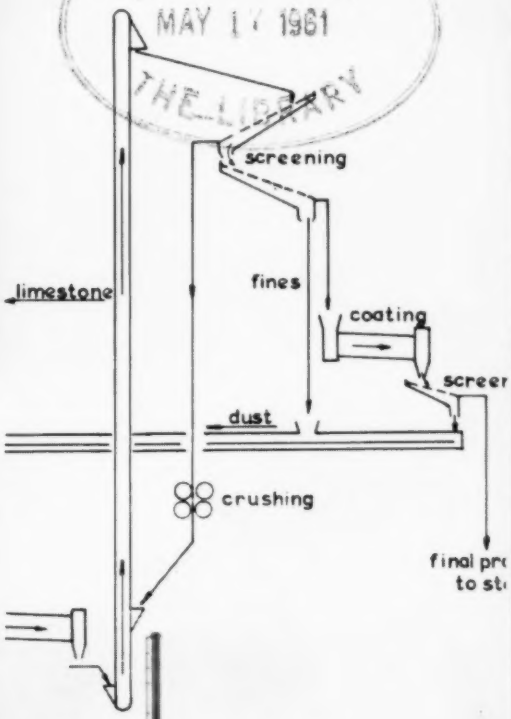
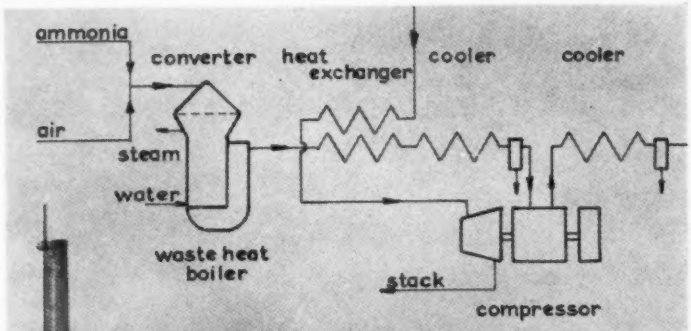
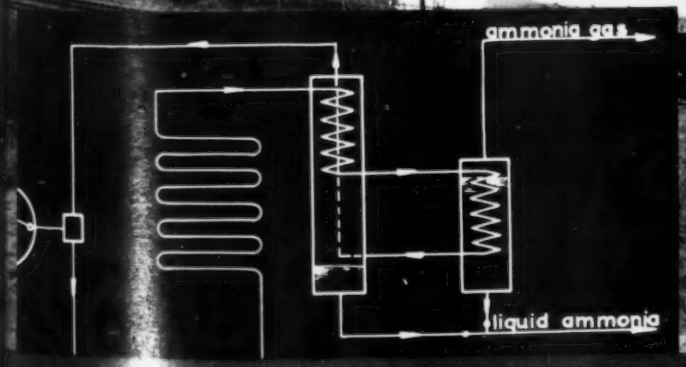




UNIT OPERATION REVIEWS



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Fluidization *(page 327)*

BCE 9490 for further information

BURSTING DISCS

LOW AND MEDIUM PRESSURES

"Delanium" Graphite Bursting Discs are manufactured in two ranges, a LOW PRESSURE range covering pressures from 1–4 psig, and a MEDIUM PRESSURE range covering 5–400 psig, with orifice diameters of 2 in.–12 in. and 1 in.–12 in. respectively.

"Delanium" bursting disc assemblies are completely resistant to the corrosive attack of most acids, alkalis and solvents at temperatures up to 160°C. Manufactured from a high-quality graphite, the discs are precision ground to close tolerances and subjected to rigorous permeability and bursting-pressure tests to ensure accuracy of burst. The discs will withstand thousands of pressure applications at 75% of stated burst pressure without loss of accuracy. The design of the discs and vacuum supports assures ample relief opening on rupture for the rapid escape of excess pressures.

Replacement discs are quick and easy to install and for standard pressures are readily available from stock. Holders and vacuum supports costs are generally initial costs only and replacement discs are inexpensive.

RANGE OF DISCS AND PRESSURES

Orifice Diameter	Bursting Pressure psig
1 in.	20-400
2 in.	4-200
3 in.	3-150
4 in.	2-100
6 in.	1-75
8 in.	1-40
10 in.	1-30
12 in.*	1-25

* Larger diameter discs on application.

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DIGEST OF INDUSTRIAL AND TECHNICAL DEVELOPMENTS

Synthetic Diamonds

SYNTHETIC diamonds over one carat in size, weighing about 0.0025 oz, have been made in the research laboratories of the U.S. General Electric Company. These large synthetic diamonds are dark in colour and, being flawed, not at present suitable for industrial use, but research is continuing in the hope of improving them.

Small synthetic diamonds—first made by G.E. in 1955—have been in commercial use since 1957. Under controlled conditions they can be produced to specific requirements for cutting, polishing and grinding operations. They also have valuable applications as semiconductors, particularly as temperature-sensitive elements, being capable of detecting temperature changes of 0.05°C.

The General Electric process is based on the use of a molten metal catalyst—chromium, manganese, iron, cobalt, nickel, ruthenium, rhodium, palladium, osmium, iridium, or platinum—and operates at pressures in the range 800,000-1,800,000 psi and temperatures of 2,200°-4,400°F. Without the catalyst, it is estimated that a pressure of 3,000,000 psi and a temperature of over 7,000°F would be required for the transformation of carbon into diamond.

The essential equipment comprises a small cylinder filled with graphite and layers of the catalyst metal. Pressure is built up in the cylinder by tungsten carbide pistons, and electrical heating melts the catalyst and frees carbon atoms from the graphite. As the molten catalyst spreads into the graphite, alloying with it, a thin film forms at the leading edge. Just behind the film the carbon diamonds realign themselves to form diamonds. The exact role of the catalyst film is not thoroughly understood. It is essential for the production of diamonds but occasionally the process yields graphite instead of diamonds. Tantalum is a particularly effective catalyst for inducing the growth of small diamonds—but not in all circumstances.

The best results are obtained when using pure graphite as starting material. The shape of the diamond crystal obtained varies with temperature: cubes predominate at the lower temperatures, mixed cubes, cubo-octahedra and dodecahedra at medium temperatures, and octahedra at high temperatures. Colour varies from black at lower temperature through dark green, light green and yellow to white at the highest temperatures.

Advantages of Electronic Instruments

THE advantages of electronic systems for automatic control for large installations, as compared with conventional pneumatic systems, have been put forward by MR. E. I. LOWE, Chairman of the Instrumentation Advisory Committee of the Association of British Chemical Manufacturers. Electronic transmission eliminates expensive runs of air lines; and, consequently, also eliminates troubles arising from water accumulating and freezing. Electronic controllers are readily combined in complicated installations, and they can be expected to be more sensitive than older types of controller. Although in some instances the cost of electronic instruments is higher than the equivalent pneumatic equipment, the installed cost will be less, and maintenance should be simpler and cheaper.

MR. LOWE is "sold" on electronic instrumentation as a result of a recent visit to a new oil refinery at Rotterdam equipped with an American electronic measurement and control system. The whole plant, including two 75,000 lb per hour steam generators, is remotely controlled from a 50 ft square central control room by six to eight operators. The refinery covers a large area, and the design of the control system has been greatly simplified by the use of electronic instruments. The largest control loop is 1500 ft—a tough proposition on a pneumatic system.

Maintenance costs are very much less than those of a pneumatic system, but in this installation considerable troubles were experienced at start-up because the installation contractor was not familiar with the high standards required for this type of work. Such difficulties could be avoided if the instrument manufacturer contracted to supply, install and commission the equipment.

Isotope Techniques for Engineers

THE value of radioactive tracer techniques for studying the kinetics of complex chemical reactions is well known. Almost equally important is their application to engineering problems of flow and movement, some of which have been reviewed recently by DR. J. L. PUTMAN of the Wantage Research Laboratory*.

A minute quantity of radioactive tracer added to a bulk of material reveals its complete flow pattern through a processing plant. The method has been adapted to study the flow distributions in fluidised beds by the use of labelled granules. Flow patterns of solutions can be similarly measured, using radioactive solutions. Sodium-24 has proved greatly superior to fluorescent dyes for investigating effluent distributions in the sea—notably, tidal movements of effluent from Chapelcross.

Tracer methods for measuring flow in pipelines have the advantage of being absolute and introducing no flow restrictions, and are capable of accuracies better than 1 per cent. Obstructions to flow can be located by introducing a gamma-emitting tally into the system. By introducing a radioactive source into the rotor of a conventional rotameter flowmeter, remote indication or a continuous record can be provided by a fixed radiation detector. Radioactive leak detection has been developed for internal leaks in heat exchangers and for the internal pipe of the Winfrith effluent pipeline, as well as for buried watermains and drains.

Similarly radioactive gases are being used for monitoring gas flow rates in blast furnaces, using Krypton 85 as tracer; for obtaining ventilation data; for finding leaks in hermetically sealed components such as transistors, and in uranium cartridge fuel elements; and on a larger scale for finding gas leaks in buried systems—not, however, in gas supply mains

because of the difficulty of preventing escape of radioactive gases into kitchens or laboratories.

Other uses for radioactive tracers are for measuring small rates of wear from bearing surfaces and cutting tools; for the autoradiographic study of alloys; and fluorescence spectrometry—this latter application giving a simple means for the rapid sorting of alloys and rough analysis. Thickness gauges relying on the transmission of beta particles are now in wide use for measuring thicknesses ranging from 25 microinches to 1/16 in of steel. The range can be extended to several inches of steel by using a gamma source in place of a beta source. A variant of the transmission gauge is used for detecting liquid level in enclosed tanks or vertical pipes—for instance, fixed gamma switches provide high and low level indication in the fluidised bed reactor of the uranium tetrafluoride plant at Springfields. Collimated beams of gamma rays provide a means of alignment in building construction. Transmission gauges can be calibrated to measure bulk density, for instance, of slurries, and may be sensitive to changes as small as 0.1 per cent. Developments of this type of instrument are used for checking the consistency of moulding sand, for measuring the compacting of foundations, and for monitoring the water content of setting concrete.

Gamma radiography is now the accepted technique for flaw detection in welded assemblies in the field, and in Denmark the technique is also used for checking the reinforcement of concrete beams and for the inspection of reactor shield elements too thick for normal radiography.

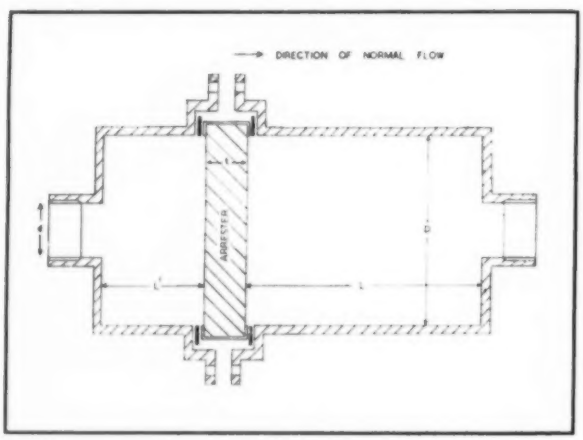
* Atom, February 1961, p. 22.

Flame Traps

ALTHOUGH much information is available on the propagation of flames in pipes, there is a dearth of literature on the design of a flame trap that will effectively stop detonations. Recent work* by the Gas Council's Midlands Research Station at Solihull has done something to fill the gap so far as concerns gas mixtures with detonation velocities not exceeding that of town gas/air mixtures.

Commercially available crimped ribbon flame arresters were mounted in housings of different shapes and sizes. The crimped ribbon type of flame arrester comprises two continuous strips of metal—one crimped, one flat—rolled on to a central former about 0.25 in diameter. Thus, right-angled triangular orifices are formed. Operating with a 1:4 town gas/air mixture, it was found that the crimped ribbon arrester, mounted either in a housing of diameter about four times the diameter of the pipeline, or directly in the pipeline, could effectively stop detonation. Great care in sealing the arrester in the housing is necessary.

Where an enlarged arrester housing is used, as shown in the illustration, pressure losses are low enough for most applications. The dimensions relating to the diagram are given below, in inches:



d	*D*	*t*	*L*
1	3.5	1.25	1-2.75
1½	7	1.5	2-8
2	7	1.5	3-9
3	14	1.75	6-15
4	14	1.75	9-24

The upstream length L' does not affect the performance of the flame trap and should be as small as practicable in order to keep the pressure loss for normal mixture flow low. The crimp size should be 0.017 in (that is, the internal height of the triangular orifices).

Where a large pressure loss can be tolerated, the arrester can be installed directly in the pipe, the table below giving the depth *t* of arrester appropriate to the pipe diameter *d*, in inches:

d	*t*
½	2.5
1	3.0
1½	3.0
2	3.25
4	3.5

The pressure loss *P* through this flame trap is given by

$$P = 0.007\ Qt/d^2$$

where Q is the rate of gas mixture flow in cu ft per hour.

Previous experimental work indicates that the depth of the arrester is a function of the flame velocity V (ft/sec):—

$$t = 1.3\ V^{0.2} - 4.4$$

Thus, to provide a basis for the design of flame traps for other explosive mixtures with detonation velocities not greatly exceeding that of town gas, the results given here may be extrapolated. The design of a flame trap for hydrogen/air mixtures on this basis is now under way at the Midlands Research Station.

* P. A. CUBBAGE, Birmingham University Chemical Engineer, Spring 1961, p.20.

A Technique for Continuous Measurement of Radioactivity

RECENTLY developed equipment for detecting radioactivity within the internationally accepted concentration range, makes use of an interesting technique.*

The water to be examined is fed to the detection unit at constant flow of 0.24 l/h. It is distributed, a drop at a time, on an absorbent paper band moving at 3 cm/hr in a chimney. Infra-red heating heats the band to about 85°C and causes the water to evaporate slowly. Flows and speeds are adjusted in such a way that the substances contained in 8 cm^3 of water are spread on 1 cm^2 of paper. The residues of evaporation then pass before an oscillating detector which measures β and γ rays and provision is made for the incorporation of a second detector for α rays. These detectors are equipped with a high surface area crystal, on account of the small amount of active residues per unit area of band, and their sensitivity (for strontium – 90) attains 5×10^{-8} $\mu C/cm^3$.

For construction reasons, the distance between the chimney and the detector is equivalent to a 6 hours delay between impregnation of the band and measurement of the activity of the residues. In order to detect high activities during this period, an alarm device may be fitted which indicates directly and instantaneously the activity of the water fed to the band. Provision is also made for indicating the various defects and failures that may arise during operation.

The plant is designed for operation at 220V, 50 Hz. The power consumption is 640W of which 500W are for heating. A minimum of maintenance is required and a high degree of safety is incorporated.

* Landis & Gyr S.A. Zoug, Switzerland.

THE STANDARD GAPMETER RANGE NOW AVAILABLE FROM STOCK

SIZE 1 ($\frac{1}{8}$ in. Pipe) | SIZE 2 ($\frac{1}{8}$ in. Pipe) | SIZE 6 ($\frac{1}{4}$ in. Pipe) | SIZE 10 ($\frac{3}{8}$ in. Pipe) | SIZE 15 ($\frac{1}{2}$ in. Pipe) | SIZE 19 ($\frac{3}{4}$ in. Pipe) | SIZE 25 (1 in. Pipe)

These illustrations (reproduced one seventh actual size) show the present range of Gapmeters and the types of connections which can be fitted.

All Gapmeters (except Size 2) have 4 inch scales, and these are designed for clarity and easy reading to 0.5% F.S.D. Calibrations are accurate to ±1.25% F.S.D. Float stability allows quick and positive reading.

Main orifice and "shunt" Gapmeter assemblies are available for pipe sizes $1\frac{1}{2}$ in. and larger. Flostat adjustable automatic flow controllers, suitable for use with Gapmeters, are now made in four sizes.

STANDARD RANGES

SIZE	FLOAT	TUBE	TAPER	WATER G.P.H. (20°C.)	AIR C.F.H. (N.T.P.)	METRIC SCALES	
1	4·35/SS	A.1	385	0·1—1		7·5—75	CC/MIN
"	4·42/D	A.1	385		0·1—1	50—500	CC/MIN
2	6·42/HS	A.2	107	0·25, 0·5, 1		1—5 LIT/HR	
"	6·30/SS	A.2	107	1, 2, 3		75, 150, 225 CC/MIN	
"	6·60/HS	B.2	155		0·2, 1, 2	0·1, 0·5, 1 LIT/MIN	
"	6·60/D	B.2	155		0·1, 0·5, 1	50, 250, 500 CC/MIN	
"	6·40/D	B.2	155		1, 2, 3	0·5, 1, 1·5 LIT/MIN	
"	6·53/D	C.2	306		0·1, 0·3, 0·5	50, 150, 250	CC/MIN
6	9·65/HS	A.6	85	1—10		75—750	CC/MIN
"	9·55/SS	A.6	85	2·5—20		200—1,500	CC/MIN
"	9·60/D	C.6	301		0·2—4	100—2,000	CC/MIN
"	9·60/D	A.6	85		2·5—25	1—12	LIT/MIN
"	9·65/HS	A.6	85		5—50	2·5—25	LIT/MIN
"	9·60/D	B.6	182		1—10	0·5—5	LIT/MIN
10	14·50/SS	A.10	44·5	6—60		0·5—5	LIT/MIN
"	14·42/D	A.10	44·5		10—100	5—50	LIT/MIN
"	14·50/HS	A.10	44·5		20—200	10—100	LIT/MIN
15	ED	B.15	31·7		30—300	15—150	LIT/MIN
"	ESS	B.15	31·7	20—200		1·5—15	LIT/MIN
"	ESV	B.15	31·7	12—120		0·9—9	LIT/MIN
19	ED	B.19	23·5		60—600	30—300	LIT/MIN
"	ESS	A.19	18·5	50—500		3·75—37·5	LIT/MIN
"	ESV	B.19	23·5	30—300		2·25—22·5	LIT/MIN
25	ED	B.25	17·4		100—1,000	50—500	LIT/MIN
"	ESS	A.25	13·8	100—1,000		7·5—75	LIT/MIN
"	ESV	A.25	13·8	80—800		6—60	LIT/MIN

This is not a complete list. Other ranges already exist for other liquids and gases, and the selection is being continually increased.

INSTALLATION: Two screwed studs allow bolting either to metal angle or panels up to $\frac{3}{8}$ in. thick. Surface mounting only is provided, but the instrument projects only a small distance.

CONNECTIONS: The end blocks are internally screwed parallel B.S.P. thread and can be fitted with nozzles for flexible pipe or compression couplings for rigid pipe. Banjo couplings permit the connection of pipes at rear of panel. The extension-pocket Gapmeters have left hand or right hand inlet and straight outlet (left hand or right hand outlet to special order). Requirements should be specified when ordering.

SIZES: The size number (B.S. 'O' Ring) identifies the mounting and all the tubes which can be optionally fitted.

FLOATS: Floats are identified by diameter and type. Type D, anodised duralumin for low pressure gases; Type HS, hollow stainless steel for liquids and gases; Type SS, solid stainless steel for liquids; Type ED, duralumin for gases; Type ESS, stainless steel giving high capacity with liquids; Type ESV, stainless steel for liquids of varying viscosity. Indicating float buttons are always P.T.F.E.

METERING TUBES: The size number is prefixed by a letter denoting taper rate, the taper stated being the length in mm. for one mm. dia. increase.

SCALES: Scales are available for common fluids in English or metric units. Special calibration requirements in small quantity are met by using arbitrary "unit" scales with conversion charts; unit scales are figured 1-10 and graduated at 0.5 intervals, the slightly non-linear spacing being designed to give reasonable accuracy when using a multiplying factor. Any scale can be supplied to meet quantity requirements.

SAFETY: No glass tubes larger than $\frac{3}{4}$ in. i.d. are used. All Gapmeters can be tested to 250 p.s.i. Glass tubes are protected by Perspex covers.

All Gapmeters can be fitted with the Flo-scan phototransistor alarm switch.

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Annual General Meeting, Annual Dinner and Dance

THE Park Lane Hotel, Piccadilly, London, W.1, Tuesday, 25th April, 1961. 10.45 a.m. in the Ballroom, Annual General Meeting. Chairman: The President, W. K. HUTCHISON, Esq., C.B.E.

The Agenda includes the minutes of the Thirty-eighth Annual General Meeting; the report of the Council; Auditors' Report; declaration of the election of Honorary Officers and Members of Council; presentation of Medals.

12.0 noon. President's Address. Industry, Science and The Chemical Engineer (open to visitors).

7.0 p.m. for 7.30 p.m. In the Ballroom. Annual Dinner and Dance. Mr. W. K. HUTCHISON, C.B.E., will preside and the principal guests will be Mr. S. P. CHAMBERS, C.B., C.I.E., Chairman, Imperial Chemical Industries Ltd., and SIR KEITH MURRAY, Ph.D., B.Litt., M.A., Chairman, University Grants Committee.

Design of Air-Cooled Heat Exchangers

DURING recent years interest in the air-cooled heat exchanger for cooling process fluids has been growing. In the air cooled heat exchanger, ambient air is forced or induced by fan to flow across a band of externally finned tubes —usually horizontal, but vertical and sloped tubes have also been used in condensing service. The tube section is carried on a steel supporting structure, with plenum chamber and fan ring, an axial flow fan and drive assembly. Surveying current practice in the design of aircooled heat exchangers, FRANK L. RUBIN of Downingtown Iron Works, U.S.A., offers the following pointers.

To limit fan noise, maximum fan tip speeds in industrial areas should not exceed 13,000 ft/min (induced draught fans) or 11,000 ft/min (forced draught fans); or in residential areas, 10,000 ft/min and 9000 ft/min respectively. Induced draught fans give better air distribution and less recirculation but are more costly to install than forced draught fans.

The design temperature of an air-cooled installation will, on an economic basis, be some 10°-20° F lower than the maximum ambient temperatures. Allowance must be made for recirculation of hot effluent air, which may be affected by the spacing of adjacent air coolers and other equipment. Winter climatic conditions (e.g. possibility of freezing the process liquid, effects of heavy rain and winds) must also be considered.

In an air-cooled unit, leaks at the tube-to-tubesheet joint can lead to fire and toxic hazards, although the large air flow through the cooler greatly reduces the concentration of the escaping fluid. Air coolers should therefore be located away from pumps, compressors, electrical switch gear, control houses, etc. Also they should not be situated where corrosive fumes and vapours from vent stacks will pass through them.

Tube-side headers are relatively small as compared with water-cooled units, and design for high pressure is relatively simple. The bond between fin and tube affects the heat transfer through the fin tube and must be considered. Vibration and thermal cycling can affect the bond resistance in various ways.

When the outlet temperatures of both fluids are the same, for a single-pass air-cooler, the mean temperature difference correction factor is 0.91, as compared with 0.8 for shell and tube exchangers. For multiple "over-and-under" passes, the factor is 0.96. Air distribution across the tube bundle is rarely uniform, and full-scale units can be expected to be less effective than small test bundles. Distribution baffles will help to equalise air flow.

When ambient air temperatures cannot cool the process liquid to the desired temperature, a combination of air-cooled and water-cooled trim cooler can be used, or alternatively evaporative cooling by spraying water into the incoming air stream of induced-draft units. Evaporative cooling can, however, bring problems of fogging, freezing and vapour recirculation.

Clarified Solutions by Reversible Cake Filtration

THE problem of filtering liquids containing solids of concentrations measured in ppm to a few percent—solids of a kind which form slimy precipitates—can often be better treated by means of reversible cake filtration rather than by depth filtration.

A filter of a type recently described* employs a special self-plugging backward feature. In operation the direction of flow of feed is reversed, through the filtering septum, without interruption of flow. The first part of filtrate formed during flow in one direction, serves as backwashing fluid for the cake on the filtering septum, when filtration is carried out in the opposite direction. In order to discharge by backwashing a given cake from its filter septum, sufficient pressure drop must be developed through the cake to separate it from the septum. This can be achieved with a relatively low flow if the cake resistance is great.

With a clear backwashing fluid, a part only of the cake will often be discharged initially and the septum will not be further cleaned. In the process reported here the feed, i.e. a plugging fluid, is used for backwashing and the cake is completely and automatically discharged at each cycle. These units are characterised by a relatively large port area, necessary for the flow of cake out of the filter, and injection moulded plates of acrylonitrile-styrene and butadiene-styrene. Any filtering media in a sheet form can be used.

The only plate size currently available has 0.66 sq ft of filtering area but sizes up to 8.6 sq ft are projected. The plates are designed for 150 psi, the cloths are supported every ¾ in. and pressure drops up to 100 psi can be used with most cloths.

The first full-scale installations of these filters were in the filtration of swimming pool waters and the clarity of the filtrate was far greater than is required in most municipal filtrations. In some cases, continuous addition of diatomite filter aid can be incorporated with larger filters.

* Judson G. Brown in a paper "Clarified Solutions by Reversible Cake Filtration" presented on March 1st to the New Orleans Meeting of the A.I.Ch.E.

Fusion Pots

THE item published under this head in our last issue may have given the impression that the use of anhydrous liquid ammonia for purifying caustic soda solution had so far not reached commercial application. The latter, however, as an authority in the field has pointed out to us, is not the case since a plant employing this principle has been in operation at the Natrium, West Virginia factory of the Pittsburgh Plate Glass Company since 1948.

It is worth noting that at least one text book also appears to be unaware of the existence of this plant, for example, in their book "Industrial Chemicals" (Wiley, 1957) FAITH, KEYES and CLARK, although referring to the ammonia treatment process, do not include this particular plant in their list of manufacturing units.

So far as the use of Dowtherm heated evaporators is concerned, the position is that several plants employ them, both in the U.S. and in Europe. Murgatroyd's in this country have, indeed, used such concentrators in their anhydrous caustic soda manufacture since 1951.

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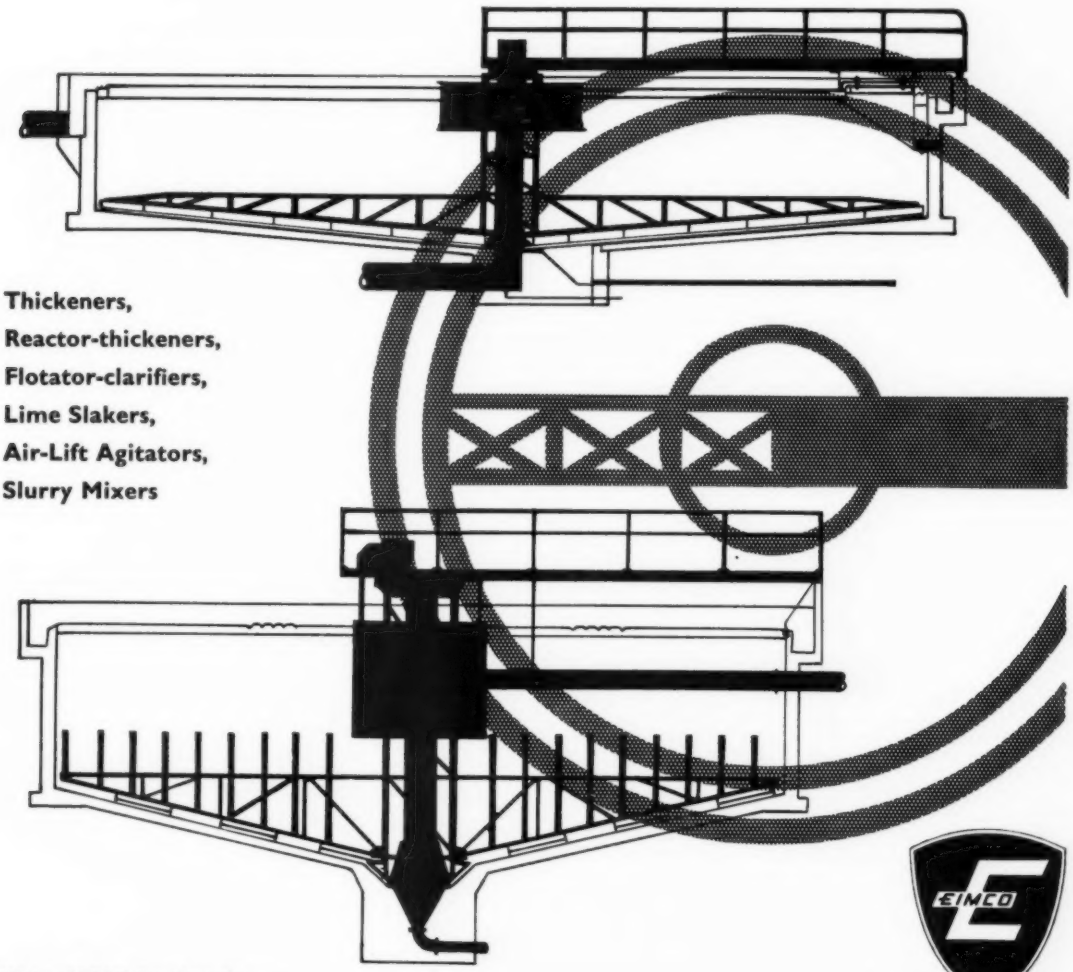

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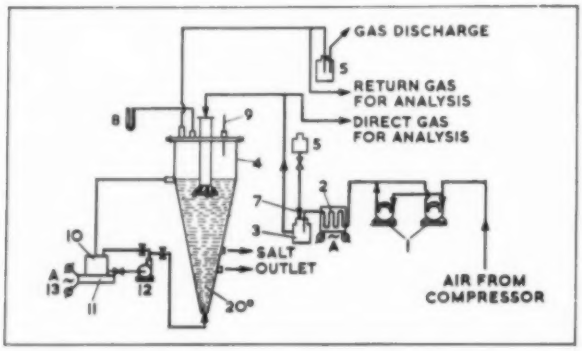
P.2699

Designing a Unit for Producing Large-Crystal Ammonium Sulphate



DIFFICULTIES have been experienced in the Soviet Union in the production of ammonium sulphate in large crystal sizes in the bubbling saturators that are currently in use there in the coke and chemical industries. With a view to solving this problem, UKhIN scientists* have studied the influence of mixing on the aggregation of crystals of ammonium sulphate and have investigated the design fundamentals of mixing devices—mechanical mixers, a gas-operated mixer, and pump-circulation of the liquid in the bath.

All the methods of mixing used gave a large salt with a predominant yield of the fractions above 0.6 mm. For industrial apparatus, the investigators recommend either mechanical stirring or using a conical saturator (20° cone) with mixing by pump circulation of the liquid. The conical saturator gives uniform distribution of the speed of the current over the cross section, and also classification of the salt with height, thus enabling salt of the required size to be selected. The mixing device should be designed to provide a liquid exchange of 300-400 times with respect to the quantity of crystalised salt.

* Coke and Chemistry USSR No. 10, 1960, p. 40.

Economics of Drum Storage and Handling

MOST drum containers for liquid chemicals made in the United Kingdom are covered by two British Standards—B.S.814 for light gauge drums up to 16 B.G. and B.S.1702 for heavy gauge drums with bodies up to 12 B.G. and 10 B.G. ends fitted with heavy reinforcement to the chimb and with rolling hoops of I section rolled steel.

Even light-weight drums are physically strong enough to make more than one trip—the 45 gallon 18 B.G. drum will make up to six trips before failure. The heavy roller hoop drum has a much longer life—for cost purposes, estimated by ICI (Billingham) at ten years life with six trips per year*.

The heavy roller hoop drum is costly to make, heavy, clumsy and occupies more space than the light-weight; it is not amenable to mechanised handling. But its rigidity and strength enable it to withstand rough handling which would destroy the light-weight drum.

Heavy roller hoop drums are not suitable for export, so that where export trade equals or exceeds home trade it is attractive to standardise on light-weight drums to simplify records and accounts, eliminating the need for return and reconditioning. Moreover the new light-weight drum has some customer appeal.

At Billingham, ICI use 45 gallon 18 B.G. bodyfiller drums handled on their hoops until after filling, when they are handled by fork trucks. The drums do roughly two trips in the home trade, are reconditioned, then lost in the export market. An exception is methanol, which is stored in heavy roller hoop drums for the home trade and 45 gallon 18 B.G drums for overseas, both being handled, laid on their sides, by crane and can hooks.

Mobiloil store lubricating oil in 40 gallon 16 B.G. body filler drums used as returnables, which are upended and stacked vertically after filling by squeeze lift trucks. Similar drums are used by Shell for lubricating oils, but are handled laid on their sides both empty and full. Shell petrochemicals are packed in 45 gallon 18 B.G. end filler drums, handled before filling in the upright on roller conveyors, and after filling on pallets by fork truck. One of the most elaborate conveyorised systems for filling and loading chemical storage drums is that of Royal Dutch Shell at Pernis.

Broadly speaking, where only hundreds of drums are handled per day, a high degree of mechanisation is not worthwhile; but where thousands a day are involved, the saving in time by complete mechanisation justifies the expenditure.

* T. B. BATTYE, Institute of Packaging Journal, March 1961, p.18.

American Standard Testing Procedures for Process Equipment

THE American Institute of Chemical Engineers have published a series of Standard Testing Procedures on heat exchangers, centrifugal pumps, impeller-type mixing equipment, and rotary continuous direct-heat dryers.

The Standard Procedure for "Heat Exchangers" is in two parts. Section 1 provides for conducting and interpreting performance tests of shell and tube-type heat-transfer equipment for comparison with the manufacturer's predicted performance; for the comparison of predictions from theoretical heat-transfer and pressure drop calculations with commercial performance, and for accumulating data on foulding resistances. Section 2 covers performance tests of shell and tube-type condensers under any set of operating conditions.

The testing procedure for "Centrifugal Pumps (Newtonian Liquids)" covers performance tests on centrifugal pumps including mixed and axial-flow types handling liquids containing no suspended solids. That on "Mixing Equipment (Impeller Type)" deals with impellers moving fluid by a centrifugal-pumping or a fluid-thrusting action and by viscous drag. It does not cover mixers for pastes or dry solids.

"Dryers (Rotary Continuous Direct-Heat Dryers)" lays down directions for the performance testing of dryers of the type in which a continuous flow of material to be dried is brought into contact with a continuous stream of hot gas, flowing either countercurrently or concurrently. Continuous cross flow or through flow (from outside the dryer cylinder walls to inside, or vice versa), is not included in this procedure.

Cheap Hydrogen

HYDROGEN of 95 per cent or higher purity can be produced at lower cost, it is claimed, in a new type of plant based on the dissociation of ammonia and the adsorption of nitrogen from the dissociated gas stream.* The hydrogen generator, developed by Armour Industrial Chemical Co. and the Dow Chemical Co., is built by The Electric Furnace Co., Salem, Ohio, and can be supplied in capacities from 350 to 10,000 scf hydrogen. A packaged 2000 scf hydrogen generator costs about 50,000 dollars and can produce 95 per cent pure hydrogen for about three dollars per 1000 scf.

The first stage of the process is the conventional dissociation of ammonia by high-temperature cracking in the presence of a suitable catalyst, the ammonia stream being preheated in a heat exchanger by the dissociated product (75 per cent H_2, 25 per cent N_2). The product gas stream is then cooled to 86°F, compressed to about 100 psi and again cooled before passing to one of three adsorbers containing charcoal and

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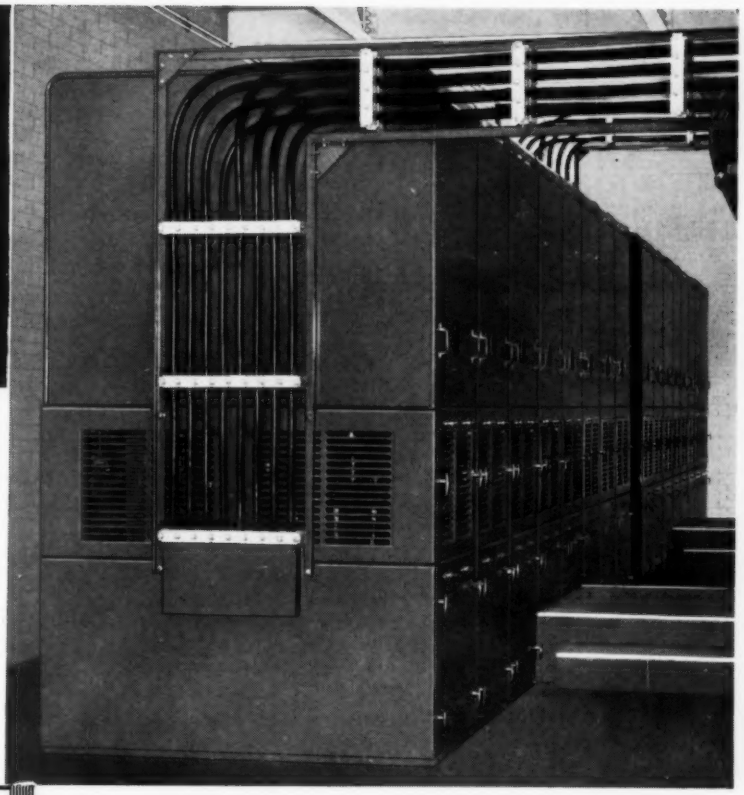

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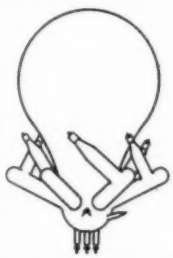

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evacuated to 10 mm Hg absolute. As soon as the adsorber is filled the inlet valve closes and the outlet valve opens releasing gas to a blower. Control is automatic. In the adsorber, nitrogen is at first rapidly adsorbed by the charcoal, then very slowly desorbed. Hence at first the hydrogen released from the outlet is extremely pure—about 99.8 per cent. As pressure falls and more gas is released, hydrogen content decreases until it reaches about 79 per cent in a typical cycle, at which point the delivery valve closes and the adsorber is regenerated by evacuation.

With an 80 sec. cycle for charging, discharging and regeneration, the product gas composite has a hydrogen content of about 96 per cent. Higher purity product can be produced by increasing the cut-off pressure on the discharging cycle. For a 95 per cent product, better than 96 per cent of the feed hydrogen is recovered. For 99 per cent purity, about 68 per cent recovery of hydrogen is achieved. For higher purities, yield drops sharply.

The cost break-down given below is based on the standard electric 2000 scfh plant and the estimated cost of bulk delivery by tank car.

Fixed cost/hr. (including interest on capital investment, maintenance, floor space rental, insurance, taxes and depreciation) based on operating year of 6,240 hr.	$1.65/hr.
Labour; 1 hr./day at $4.50	$0.19/hr.
Power; 86 kwh. at $0.013	$1.12/hr.
Water; 600 gal./hr. at $0.20/M gal.	$0.12/hr.
Ammonia; 65 lb. at $0.045	$2.92/hr.
Cost of 95% H_2 per 2000 scfh	$6.00

* Chemical Engineering, March 1961, p. 72.

Membrane Permeation

FOUR papers, dealing with various aspects of membrane permeation, were presented jointly at a Symposium on Less Common Separation Methods in the Petroleum Industry, by the Division of Petroleum Chemistry and the Division of Industrial and Engineering chemistry of the American Chemical Society.

The first paper by C. Y. CHOO and B. H. SANDERS describes the membrane permeation process, which is essentially a unit operation now in commercial use. The qualitative performance of this process may often be predicted. A number of variables affect the process and many tests are required in order to obtain actual performance data under varied conditions. The paper describes what data are needed to determine the feasibility of a given separation, and how these data may be obtained from a newly developed laboratory membrane permeation cell, which may be operated continuously or batchwise. The estimation of separation costs, and the design of a commercial installation from laboratory data, are also included.

In the second paper, R. C. BINNING presents an analysis of the separation of various types of hydrocarbon mixtures by liquid-vapour permeation. He compares this with other methods of processing and discusses results obtained on the separation of isobutane-butene alkylate, catalytic gasoline and catalytic reformate.

V. N. SCHRODT, R. F. SWEENEY and A. ROSE presented the third paper on membrane permeation of liquid mixtures, such as acetone/chloroform, carbon tetrachloride/chloroform and acetone/methyl acetate, to a vacuum through membranes such as Teflon, Cellophane and PVA. Their data indicated that hydrogen bonding has a significant and sometimes predominant effect on the separation. The substance which may be bonded most strongly to the film being selectively retarded in permeation rate.

The last paper, presented by A. S. MICHAELS, R. F. BADOUR, H. J. BIXLER and C. Y. CHOO, was a study of the kinetics of transport of the isomeric xylenes through polyethylene films. They found that polyethylene exhibits pronounced permselectivity towards xylenes in the order of ortho>meta>para, high-density polymer being more permselective than low. They also showed that polyethylene may be "conditioned" to increase its permeability and permselectivity. This may be achieved by annealing the polymer in the presence of sorbed xylene. Permselectivity is extremely sensitive to annealing temperature, sorbate content during annealing, and the molecular structure of the sorbate.

DIARY

The Institution of Chemical Engineers

May 10. (Graduates and Students Section Meeting.) Meeting of the Midlands Centre in the Main Lecture Theatre, Chemical Engineering Department, The University, Edgbaston, Birmingham 15, at **7 p.m.**

May 30. Royal Commonwealth Society, Northumberland Avenue, London, W.C.2. Symposium on Biochemical engineering.

Society of Chemical Industry

May 9. Chemical Engineering Group. Symposium on Highlights of Requirements of a New Chemical Plant Project: "Financing a New Chemical Plant Project," by K. C. P. BARRINGTON. "Selecting a Site for a New Chemical Plant Project," by Dr. J. L. MURDOCH. "Designing and Building a New Chemical Plant Project," by T. T. WHIPPLE. Assembly Hall, Royal Commonwealth Society, London, W.C.2. **2.30 p.m.**

May 26. Heavy Organic Chemicals Group. 14 Belgrave Square, London, S.W.1. **6 p.m.** Annual General Meeting. Chairman's Address, by Dr. M. A. MATTHEWS. "Planning in the U.K. Chemical Industry."

The Institute of Petroleum

May 3. "New Ideas in Welding for the Petroleum Industry." W. K. B. MARSHALL and V. I. HOLMES (Rockweld Ltd.).

The Institute of Refrigeration

May 4. The Institute of Marine Engineers, The Memorial Building, 76 Mark Lane, London, E.C.3. **5.30 p.m.** "Metals for Refrigeration and other Low Temperature Installations," by G. P. SMEDLEY, B.Eng., B.Met.

The Institute of Fuel

May 15-19. Second Conference on Waste Heat Recovery. Bournemouth. "Waste Heat Recovery from Industrial Furnaces."

The Institute of Materials Handling

May 10-12. Second International Conference on Materials Handling, Southport.

International Fair

May 19-June 4. British Trade Fair, Sokolniki Park, Moscow.

IN OUR NEXT ISSUE

Crushing and Grinding Calculations
by FRED C. BOND

The Heat Pump in Multicomponent Distillation
by D. C. FRESHWATER

A New Type of Solid-liquid Extractor
by H. L. RAMOS and R. B. ZAYAS

The Performance of Some Heat Exchangers in Chemical Plant
by F. R. WHITT

MATERIALS HANDLING CONFERENCE

THE Second International Conference organised by the Institute of Materials Handling is to take place in Southport from May 10th to 12th.

The future of industry depends to a large extent on the way in which keen overseas competition can be met and today's production methods are the vital factors in the country's ability to sell competitively.

The Conference, the second to be held by the Institute on materials handling, will provide a forum for the international exchange of knowledge and experience and the opportunity to discuss new methods and trends. It may be remembered that last year's conference brought together experts in materials handling from the Continent including Poland and the United States. Delegates were able to hear the experiences of men working in various types of handling, and to take part in lively discussions which benefited all who attended.

At this year's conference the four aspects, construction, procurement, manufacture and transport and distribution will be examined in relation to the materials handling problems in a number of industries including food, extractive (minerals) and chemical industries.

Papers to be presented include—

"Handling Raw Materials in a Heavy Industry," by H. J. STENGERT—Assistant Manager, Industrial Eng. Dept. (August-Thyssen-Hutte), Duisburg, Germany.

"Handling in Motor Manufacture," by F. J. D. SHAW—Materials Handling Engineer (The Standard Motor Co. Limited) Coventry, Warwicks.

"Transport and Distribution in Heavy Industries," by J. N. DRUMMOND—Chief Heavy Haulage Manager (Pickfords) London, England.

"A Study from the Pharmaceutical Industry," by S. B. CLARK, Head, Work Study Dept.,(Allen & Hanburys Limited) Ware, Herts.

"Standardisation and Materials Handling," by H. St. LEGER, General Secretary, International Organisation for Standardisation, Geneva, Switzerland.

"Manufacture in the Food Industry," by C. ROPER—Materials Handling Consultant and Engineer, Hamburg, Germany.

"Handling in Tin Mining," by J. L. FARRINGTON—Chairman (A. O. Nigeria Ltd.) Jos, Nigeria.

"Bulk Handling of Powders in the Chemical Industry," by F. E. D'ARCY-SMITH—Managing Director (Polysius Ltd.) Ascot, Berks.

In addition, two series of Works Visits have been arranged on the first and second days of the Conference to a number of important factories and other installations in Cheshire and West Lancashire.

Further information may be obtained from the Institute of Materials Handling, 32 Watling Street, London, E.C.4. Telephone City 7046.

PROFESSIONAL APPOINTMENTS

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For Box Numbers reply to BRITISH CHEMICAL ENGINEERING, Drury House, Russell Street, Drury Lane, London, W.C.2.

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Applications are invited for a position of Assistant Chemical Engineer. Applicants should be aged 25-35. Preferably with A.M.I.Chem.E. or recognised equivalent, and should have some practical experience of design and operation of chemical plant. The position offers good prospects of advancement in an old established but progressive Company, located in North Eastern England. Contributory pension scheme, five-day week and canteen facilities. Apply giving full details of education training and experience to Box No. 101.

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DUTIES.—The R. & D. Division, under the direction of the Superintendent and Assistant Superintendent, has a total authorized staff of 46, of whom 16 Research Metallurgists work in teams or individually under the guidance of four Senior Research Metallurgists on a wide variety of projects. Current projects include flotation of new copper ores, fluid bed roasting of concentrates, leaching and electro-winning development work on copper concentrates, plant tests on ball milling and a number of new developments for the recovery of copper, lead and zinc.

In addition to well-equipped Metallurgical, Mineralogical and Analytical Laboratories, the Division maintains and operates a pilot plant in which most of the Group's current operations, as well as new processes, can be simulated on a 10-20 tons per day scale. Metallurgists are sometimes required to undertake shift work on the pilot operations for campaigns of a few weeks.

Promotions and transfers within the Group are frequent and it is the Group's policy to give men experience in a wide range of metallurgical operations.

Some of the posts require men with some industrial experience but recent graduates will also be considered for practical training.

PAY, etc.—The commencing basic salary will be determined by qualifications and experience but will not be less than £1.131 per annum (for one year of appropriate experience), plus a bonus, varying with the prosperity of the industry, which is at present approximately 40 per cent of basic salary, and a variable cost-of-living allowance, which is at present about £60 per annum. Excellent fully serviced, modern housing, complete with basic furniture, refrigerator, etc., is provided at a nominal rental. There are also generous pension, life assurance and medical benefits. Leave varies between 48 and 51 days per annum, depending on salary, and may be accumulated for up to three years. Air or sea passage for the successful candidate would be paid by the company and assistance may be provided towards other importation expenses. Income tax rates are low.

GENERAL INFORMATION.—Kitwe is situated on the Central African plateau at an altitude of 4,100 feet above sea level and consequently enjoys an equable, healthy climate of dry cool winters with a rainy season moderating summer temperatures.

Ample all the year round facilities for all the usual sports are available. Two modern cinemas offer daily programmes. Numerous recreational societies are active in the town, which has a population of about 12,000 Europeans. A television service is expected to commence in a few months.

Education at the Federal Government schools is free. Several modern and well-equipped primary schools cater for the younger children. The boys' high and girls' high schools prepare pupils for the usual school leaving certificates and university entrance examinations.

APPLY BY AIRMAIL TO The Secretaries, P.O. Box 172, Kitwe, Northern Rhodesia, stating age, marital status, qualifications, experience record, availability, and the names of two referees, and enclosing a recent photograph.

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A degree of Chemical Engineering or membership of an appropriate technical institute is desirable, and the age group preferred is 30/35 years, but applications will be considered from candidates holding Higher National Certificate or the equivalent and established practical ability.

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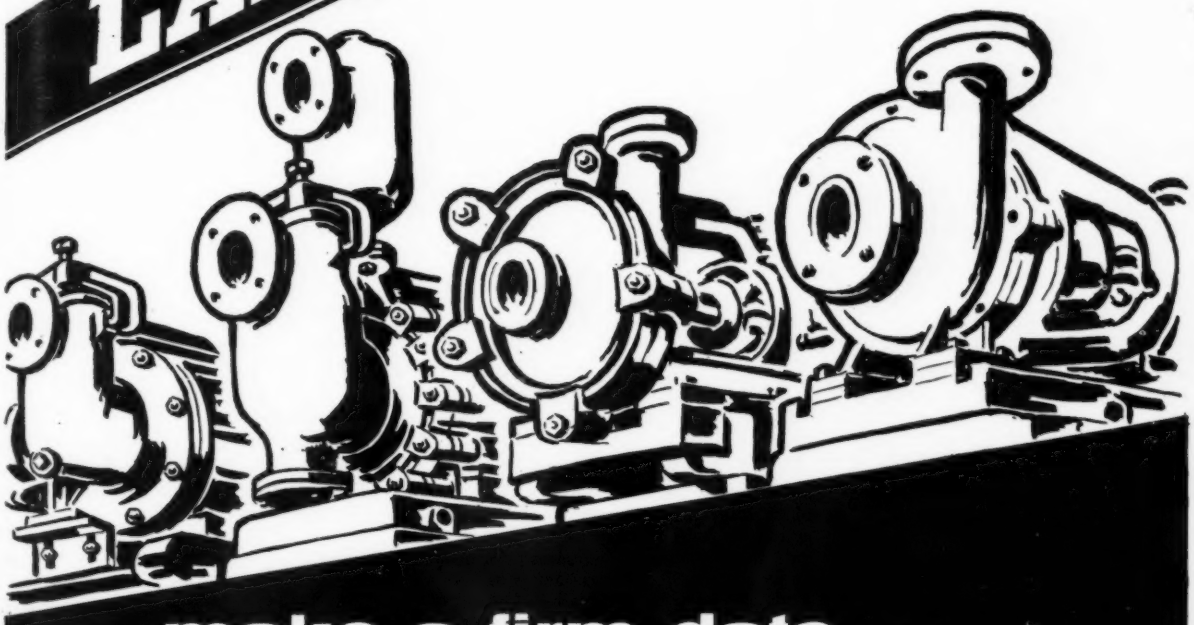

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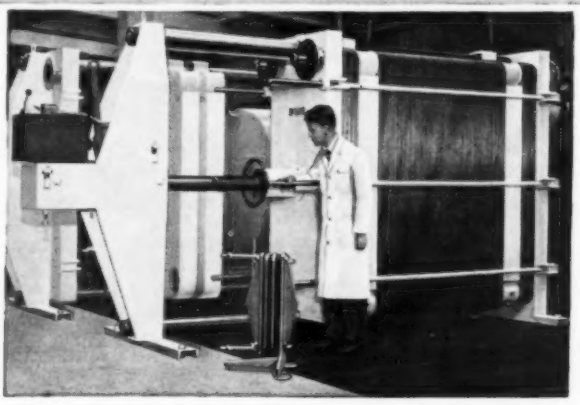

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Review Issue

THE present issue of this journal, marking the fifth anniversary of its inception, presents in an easily-digestible form reviews of progress that has been made in a few of the important branches of chemical engineering.

One of our reviews, by L. K. DORAISWAMY, surveys the field of reactor kinetics and examines the present state of reactor design methods. He traces the development of the subject and focuses attention upon important landmarks such as the concept of macro- and micro-kinetics introduced by VAN KREVELEN. In considering reactor design, DORAISWAMY examines theories of mass transfer and concludes that the early two-film theory of HATTA and WHITMAN can be used without loss of accuracy for design purposes. On the question of hold-up in reactors, he clearly shows the importance of the concept of residence time distribution; for example, the loss of yield arising from the retention of a fraction of a product in a reactor beyond the time corresponding to maximum conversion. He also points to the reactor situations which require prediction of residence time distribution and indicates the types of reaction and reactor for which it can be estimated. A feature of this review is the awareness of the design function, something which is all too frequently overlooked.

G. V. JEFFRIES covers the extensive field of mass transfer which he conveniently subdivides into four groups, the first being devoted to fundamentals and the remaining three to the familiar unit operations of distillation, absorption and extraction. From this review one can readily learn that there have been no startling developments in fundamentals; also the considerable amount of work on bubbles has yielded correlations of limited application only, and certainly not to the bubble masses encountered in industrial equipment. Throughout this review its author shows an appreciation of the problems of designers of mass transfer equipment, and in the case of simultaneous absorption and chemical reaction it is interesting to learn that cocurrent operation is advantageous when the chemical reaction rate is high.

At the outset of the review on fluidization J. S. M. BOTTERILL explains why there is so much interest in the dynamics of fluidized systems and why the problem of bubble formation in gas fluidized systems is the subject of a great deal of research. Consequently, in the review considerable attention is given to bed dynamics including the formation of bubbles and, in addition, mass and heat transfer in fluidized beds are surveyed. In the latter connection it is becoming increasingly apparent that the localization of temperature gradients within turbulent beds contributes considerably to their thermal properties.

J. NIJMAN devotes his review to a subject much neglected by chemical engineering research—crushing and grinding. Apart from the references to surveys of existing theories, to a number of valuable original contributions and its useful treatment of industrial applications, this review refers to an interesting Chinese work. This deals with the movement of charge in a ball mill, and its author evolves a technique for calculating the optimum ball load as a function of rotational velocity. Also of interest in NIJMAN's contribution are the references to theories of jet milling, a subject seldom treated in the English literature.

One final review is the one by J. W. CARTER, on adsorption. Readers will recall that CARTER contributed three important articles to this journal last year on the subject of adsorption drying. His review describes present-day adsorption techniques for process separation purposes, including the recently-developed molecular sieves and permeable membranes.

But for limitations of space, it would have been possible to embrace many more aspects of the branch of engineering science to which this journal is devoted. A way out of this difficulty—a temporary solution—is to review most of the subjects at two-yearly intervals. Consequently, our next review issue will embrace some of the important topics not dealt with in the initial review issue, such as fluid dynamics and heat transmission.

In attempting to decide upon suitable subjects for review, we have been influenced not only by what is traditional to chemical engineering but also by the demands which we think are likely to be placed upon chemical engineers in the future.

It is appreciated that without chemistry there would be little point in the existence of chemical engineering as a separate discipline. In view of this dependence, we have to be particularly sensitive to developments in chemistry and it would, therefore, be useful to acquire, without excessive effort, a view of recent advances of the kind most likely to affect chemical engineering. Such developments may be expected to take place in the fields of surface chemistry, kinetic theory, reaction mechanisms, transport phenomena and others. It is very likely, too, that in the future there will be considerable interest in high-temperature conditions typified by flames, plasmas and shock waves, and, at the other end of the scale, there may be comparable interest in very low temperatures including reactions, and properties and behaviour of substances at such extreme conditions.

Reviews offering the reader useful perspective of the important developments in science seem well worth while, particularly since it is from this direction that new principles and materials will often come.

In selecting other topics for review we are also governed by the fact that chemical process design will, in the future, require greater application of what is understood by that inelegant term "systems engineering", undoubtedly one of the most difficult fields for the chemical engineer to traverse. In addition, there are the economic aspects of chemical engineering, of which optimization especially is receiving a great deal of attention at the present time and—not to be ignored—developments in various types of equipment and in design methods. It may also be useful to assemble a digest of experiences of plant operation in industry and knowledge from bordering branches of engineering, in particular mechanical engineering.

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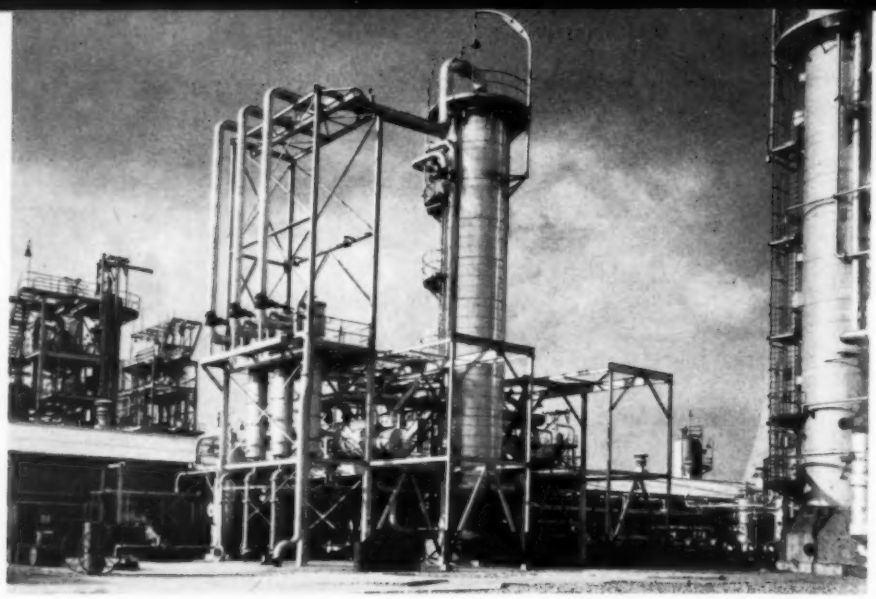

A view of a diethanolamine unit for removing H_2S from refinery gases.

MASS TRANSFER

Research papers published on mass transfer phenomena during the past year have been abstracted and are briefly discussed under the headings of fundamentals, distillation, absorption and extraction. The work discussed under the various headings was selected as being typical of the field of investigation and illustrative of trends in present-day research.

In the field of fundamental mass transfer considerable study continues to be devoted to surfaces, plane and spheroidal, and to the effects of surface active agents on mass transfer rate. In all the other sections a wide range of research continues, varying from phase equilibria and the assessment of different contacting equipment to the study transients and batch operation.

by G. V. JEFFREYS

THE past twelve months has again been a period of intensive research in fundamental and applied mass transfer. Our knowledge is being rapidly extended by continued study of the different aspects of the subject, ranging from the very fundamental reports on mechanism to the completely applied papers dealing with commercial equipment. In general, investigations continue along lines initiated in the recent past, although one or two new approaches are being considered. These will be discussed below where it has been thought convenient to sectionalize the review into:

(a) Fundamentals;
(b) Distillation;
(c) Absorption;
(d) Extraction.

Fundamentals of Mass Transfer

(1) *Diffusion Coefficients* continue to interest workers. Thus BERRY and KOELLER[6] have determined the average diffusion coefficients of the binary systems hydrogen-nitrogen, nitrogen-ethane, and nitrogen-methane at very high pressures by the method proposed by LOSCHSCHMIDT (1870). They found that the experimental results diverged below those predicted by the LENNARD-JONES model (with THORNE's dense gas correction) based on kinetic theory calculations, and suggest that a better prediction is obtained from the SLATTERY and BIRD (1958) reduced state correlation. The results reported must be very reliable, because of the extensive precautions taken to equalize the pressure of each component in each half-cylinder prior to mixing, the uniformity of temperature during each experiment, and the elimination of initial convectional turbulence on mixing.

A new approach to the determination of the rate of diffusion of a gas through a porous solid has been made by FLEMING,[25] who determined the effective diffusivity of krypton through porous silica by a new tracer technique. The procedure described has many advantages, being fast and economic, as it is unnecessary to know the specific activity or the exact quantity of tracer; and in most cases the data are correlated by a simple graphical procedure.

(2) *Mechanism.* Some worthy contributions have been made to our understanding of the mechanism of mass transfer across an interface. Thus DAVIES and WIGGILL[16] employed an unstirred diffusion cell and observed the rate of acetic acid and diethylamine transfer across a stationary water oil interface when the interface was scrupulously clean, and when monolayers and polymolecular films had been inserted. They found that neither the clean interface or the various monolayers offered resistance, but the polymolecular films gave rise to considerable resistance. All the systems studied tended to emulsify at the surface, but this did not impede mass transfer.

Another excellent theoretical paper has been presented by STERNLING and SCRIVEN,[73] who explain the formation of interfacial emulsions as being due to hydrodynamic instability or interfacial turbulence. The analysis presented by

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these authors shows how some systems may be stable when solute transfer is in one direction, yet unstable when transfer is in the other direction. The basis of their theory is the long known but much neglected Marangoni effect which postulates that movement within interfacial layers is caused by longitudinal variations of interfacial tension.

Further work on the mechanism of transfer has been reported by MANLEY,[51] who studied the rate of growth and collapse of air bubbles in distilled degassed water by estimating the effective diffusion coefficient for air through the bubble walls. The experimental results obtained are low, and the explanation suggested is that of the presence of an organic skin effect which impeded transfer. UDANI and GORDON[78] also studied the effect of surface films on the rate of mass transfer by estimating the rate of evaporation of water through films of dodecyl, myristyl, cetyl and stearyl alcohols. However, these investigators passed dry air over water in a beaker while both phases were agitated. They, too, found that in order to effect a significant reduction in the rate of transfer it was necessary to deposit a polymolecular film of fatty alcohol on the interface.

The above papers infer that with a clean interface or in the absence of surface-active agents equilibrium exists at the interface; whilst the insertion of a polymolecular layer between the two phases implies placing a resistance of finite thickness at the interface, and therefore the rate of mass transfer would be expected to be reduced. Equilibrium at the interface is contrary to the views of EMMERT and PEGFORD (1954), who stated that interfacial resistance was due to a "bouncing back" of some of the solute molecules that struck the surface. RANZ and MARSHALL (1952) and WARD and BROOKES (1952) and many other workers subscribe to the concept of interfacial resistance.

Great care should be taken when studying the effects of surface layers, because they tend to change the wetting characteristics of the fluid with respect to the containing vessel, thereby changing the interfacial area, and what appears to be a polylayer could well be monomolecular.

In a slightly different aspect of mass transfer research MCCARTER and STUTZMAN[52] investigated the evaporation of pure liquids into air streams in a wetted wall column in order to evaluate the additional resistance to transfer that may be presented by eddy diffusion, and to compare the film concept with the physical approximations of fluid mechanics. They found that the contribution of eddy diffusion to mass transfer was negligible, but that good agreement was obtained between film thickness calculated from mass transfer and molecular diffusivity; and gas phase laminar and buffer layers calculated from fluid mechanical principles. They concluded that in packed towers, where distances in the turbulent phase are shorter, transfer between phases depends almost entirely on molecular diffusion.

Eddy diffusivities in gases and in liquids have also been studied by FLINT *et al.*[26] These workers examined the turbulent diffusion from a point source on the axis of a 3-in. pipe by injecting hydrogen or carbon dioxide into a turbulent air stream, or potassium chloride into water. The eddy diffusivities calculated from the experimental data was correlated by plotting E/2a Uc.V.Re. The results obtained did not agree with those of previous workers and is probably due to the difficulties of measurement for small diffusion times.

(3) *Droplets and Bubbles.* The hydrodynamic behaviour and the rate of mass transfer to and from bubbles, drops and solid spheres continue to occupy a prominent place in fundamental mass transfer research. This is to be expected, because a large number of chemical engineering operations depend on mass transfer between systems of spheres and their surrounding fluid.

Hydrodynamic studies of bubble formation and rise have been reported by POUTANEN and JOHNSON,[64] who observed profiles during the formation of nitrogen bubbles in water, with the intention of correlating the area as a function of bubble volume and time. An empirical equation was fitted to their experimental results, and they also presented a correlation of limited applicability for the rate of rise of a chain of bubbles through a viscous oil.

By far the greatest amount of research in this field has been devoted to mass transfer and the work of GRIFFITHS[29] deserves mention. This worker employed the well-known technique developed by RANZ (1952) of suspending a droplet from a capillary in a duct, and as the droplet dissolved in the surrounding flowing fluid its size was maintained constant by feeding liquid through the capillary from an ultramicro burette. In some runs the rate of change of the globule diameter was employed to measure rate of mass transfer. From the experimental results he proposed semi-theoretical formulæ based on dimensionless parameters for the rates of solution of drops and bubbles under forced convection conditions. The second paper of note is that of JOHNSON and HAMIELEC,[40] who determined the rates of transfer n-butanol, c-hexanol and ethyl acetate into circulating and oscillating water droplets. The allowances proposed by these authors in 1958 for "end-effect transfer" has been extended, and the experimental results compared with predicted rates obtained from the KRONIG-BRINK (1950) mechanism and the HANDLOS-BARON (1957) mechanism. These mechanisms or models were compared in terms of the KORCHINSKI correlating factor (CALDERBANK and KORCHINSKI, 1956) when the HANDLOS model showed promise.

Finally LINTON and SUTHERLAND[48] and also STEINBERGER and TREYBAL[72] investigated the rate of mass transfer from benzoic acid spheres to water. From the experimental results LINTON *et al.* proposed a general expression based on boundary layers for overall transfer which was approximate. On the other hand, STEINBERGER's correlation was based on statistical analysis and attempted to separate the natural and forced convectional processes.

In conclusion, it may be stated that whilst our store of knowledge is being increased no startling advances or techniques have been proposed this year, and most of the work reported on bubbles and other globules continues on the familiar theme. Numerous correlations of limited applicability have been proposed which usually are functions of dimensionless groups. However, the possibility of being able to extend these to masses of bubbles as encountered in commercial equipment is remote.

Distillation

(1) *Vapour-liquid Equilibrium.* Research in vapour liquid equilibrium continues to flourish, and many new equilibrium stills have been described. Probably the most versatile is the one suggested by OTHMER *et al.*,[61] which was designed with auxiliary interchangeable parts, thereby permitting a comparison of three major types of still. The unit was tested on the partially miscible systems toluene-water and chloroform-water. ELLIS and GARBETT[22] have also designed an equilibrium still for studying heterogeneous systems. They tested their apparatus on four binary, partially immiscible systems and the experimental results were satisfactorily correlated by separate equations for the miscible and immiscible regions respectively and also on an overall basis by the 4 suffix-VAN LAAR equation. A third still suitable for studying partially miscible systems has been designed by ORR and COATES.[58] This piece of equipment is all metal of the recirculation type. It can be used over a large range of pressures for miscible and immiscible systems.

Two other simpler equilibrium stills have been described which are suitable for work of moderate accuracy. The first, proposed by HEERTJES,[32] generates the vapour and allows it to cool under controlled conditions so that equilibrium may be attained. The second by HORVATH[36] depends on

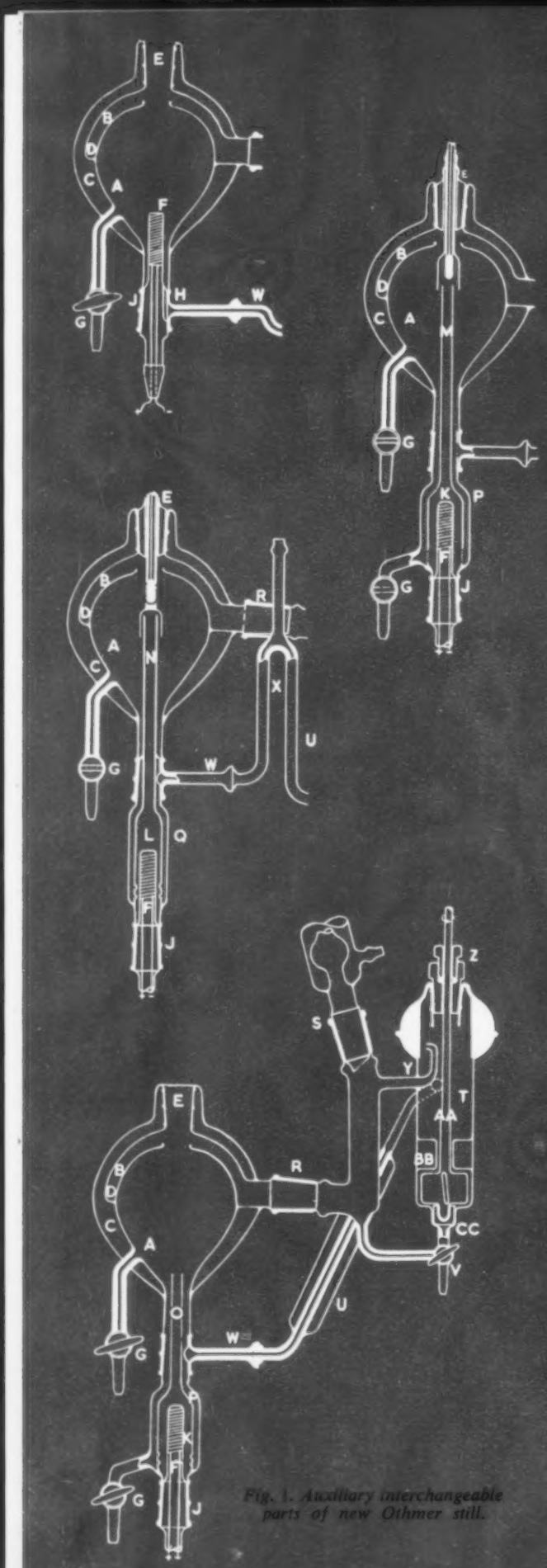

Fig. 1. Auxiliary interchangeable parts of new Othmer still.

boiling the liquid under total reflux conditions and periodically sampling the vapour and liquid by hypodermic needle samplers. The author acknowledges the fact that vapour generated may not always be in equilibrium with a boiling liquid mixture. However, he claims that this type of still is useful for systems forming two phases on condensing. The reviewer fails to see the advantage of this if the liquid and vapour phases are not in equilibrium.

Theoretical and experimental vapour liquid equilibrium studies have also been published. In an experimental study RAMANUYAN and LADDHA[67] used an Othmer still to examine the effect of glycol on the volatilities of ethyl alcohol with respect to water. Results showed the disappearance of the binary azeotrope at the concentrations of glycol studied. Theoretical aspects of this field of study have been considered by ALDER *et al.*[1] who have developed methods assessing equilibrium data for thermodynamic consistency when conditions are such that the more volatile component is above the critical point. The basis of the method is the rigorous form of the Duhem equation. Also BENNETT *et al.*[4] have examined the techniques of solving equilibrium flash vaporization problems and they have also developed a new technique. The older method of expressing the vaporization by a single equation with multiple roots which had to be solved by an iteration process has been rephrased as a differential equation which was solved on a digital computer.

Finally, JOHNSON and FURTER[39] studied the "salt effect" on the vapour liquid equilibria of three aliphatic alcohol water systems. They presented vapour liquid equilibria for the systems methanol-water, ethanol-water and n-propanol-water, each saturated with inorganic salts, and proposed a simple equation to represent the "salt effect". The theoretical significance of the equation has been ascertained in relation to the components of the system.

(2) *Distillation Column Design and Performance* have been studied intensely and eight papers are discussed which illustrate the trends in which present research is being directed. On a small scale ELLIS *et al.*[21] compared the efficiency of a 6-in. perforated plate column with an Oldershaw when both are operating under reduced pressure. They show that overall efficiency and film resistances are little affected by pressure. A second paper presenting experimental results is that of KUZMINYKH and RODIONOV,[46] who investigated the effects of gas rate and the foam structure of water on a perforated plate by estimating the oxygen desorption rate at different liquid heights. This paper is typical of other Russian papers on foam structure (E. G. NIKOLAEV, 1958) in which a column has been operated in the "emulsified flow" region near flooding.

The remaining papers are of a theoretical nature, but are nevertheless worth-while contributions, particularly TOOR and BURCHARD,[76] who present a method of predicting ternary component plate efficiency from a knowledge of each binary efficiency. The basis of their derivation is the film model of transfer combined with the equations of steady-state diffusion in a ternary gas mixture. Another interesting paper has been given by SCHUBRING[69] describing the use of the IBM 705 electronic computer to calculate the number of plates necessary for the separation of non-ideal and azeotropic binary mixtures. The author states that the number of plates can be calculated as a function of reflux or boil-up in 15 sec to 5 min per problem. LYSTER *et al.*[50] also used a digital computer to solve equations for estimating the total reflux and total reboil in a conventional continuous distillation. The equations were based on the convergence method and are capable of solving situations involving side streams.

Interest in bubble-cap spacing is shown by GYOKHEGYI,[30] who discussed a new method of estimating the vapour capacity of a bubble cap. The usual features of bubble-cap

design have been combined into two mathematical expressions in which cap spacing is the limiting factor and equations for optimum bubble cap spacing at total slot opening are derived. This paper is a most useful contribution.

An interesting paper on packed columns giving H.E.T.P. values has been published by BILLETT,[8] who has utilized previous experimental data of KIRSCHBAUM to establish an empirical equation predicting H.E.T.P. values for packed rectifying columns. Predictions by this author's method are quoted and compared with the well-known relation by HANDS and WHIT (1950).

Equipment. A number of varied papers on equipment have been published recently. Thus OTHMER[59] describes a 10.5-in.-diameter column containing three special-type trays that rotate in such a way that the ascending vapour is compressed as it passes through each plate. Hence it is possible to operate a column with zero pressure drop.

Three other papers have been published on plates. One, by MELICHAR,[52] discusses the author's experience in operation and design, but most of the information given has appeared before. A second, by KILGALLON and STREIGHT,[42] discusses the use of plastic trays which are self-sealing against the column walls. The idea of plastic trays was proposed by GARNER *et al.* (1956) and this paper does not propose anything new. Finally, LOW[49] gives performance data on the "Flexitray". They show that the capacity equals that of a well-designed sieve tray, and the efficient operating range exceeds that of most bubble-cap trays.

Finally, Metal Propellers Ltd.[53] describe a new type of reflux divider whose principle of operation depends on the liquid reflux flowing through two ports whose relative width can be varied. The reflux ratio is controlled by a lever, and any value from zero to infinity is possible.

Plate Hydrodynamics. Two papers of note have been published on this subject. The first, by KIRSCHBAUM[44] gives an account of experimental work carried out on 75-cm-diameter bubble cap and sieve plate columns using ethanol-water mixtures. The liquid depth was varied from 30 to 5 mm in the former case and from 20 mm to zero in the latter. KIRSCHBAUM found that the vapour penetration depth had little influence on separation but a decisive effect on loading.

A most welcome paper on the flooding capacity of turbo-grid trays has been presented by FÖLDES.[27] He gives a correlation based on previously published work which should be suitable for calculating turbo-grid tower diameters. The author claims that the maximum deviation of the correlation is ± 20 per cent.

Batch Distillation. Studies reported on batch distillation include two papers by MOLYNEUX[54, 55] and one by HUCKABA and DANLY.[37] The first two papers discuss batch distillation in packed columns from the point of view of channelling, heats of mixing and thermal losses. The account is supported by an example of the design of a phenol purification still.

In their highly rigorous paper, HUCKABA and DANLY have developed differential difference equations describing the transient process, and offered two methods of solution, one by hand calculation and the other by digital computer. This paper can be added to ROSE (1950), COLBURN (1951) and JOHNSON'S (1950), which are classical on this topic.

Azeotropic and Extractive Distillation. The papers recently published on these aspects of distillation are descriptive or discussive in type, and make little contribution to the advancement of our knowledge of extractive distillation. These remarks may be applied to the publications by GESTER,[28] which, as the author states, is merely a review, and by COATES[13] which follows the same lines. On the other hand, KUMMERLE[45] does discuss the influence of the addition of a solvent to modify the activity coefficient.

Instrumentation. While this is part of a wider field in its own right, mention should be made here of the paper of

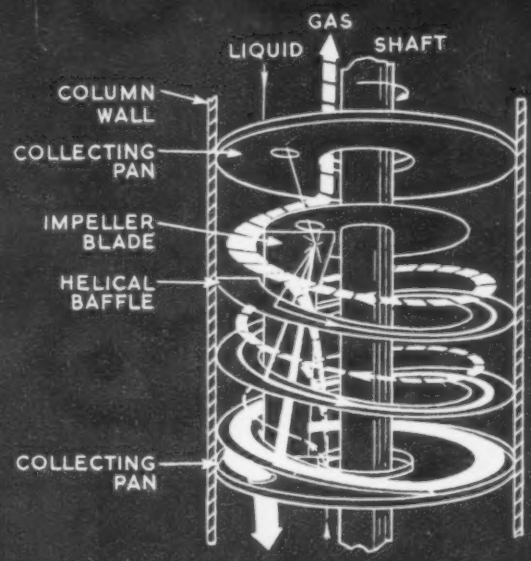

Fig. 2. Rotating distillation plate with zero pressure drop.

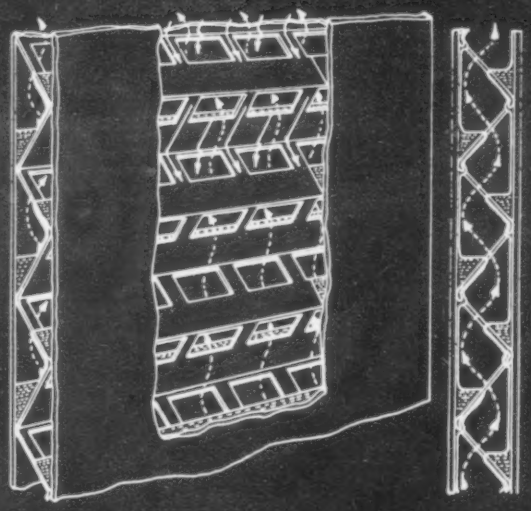

Fig. 3. Overflow packing.

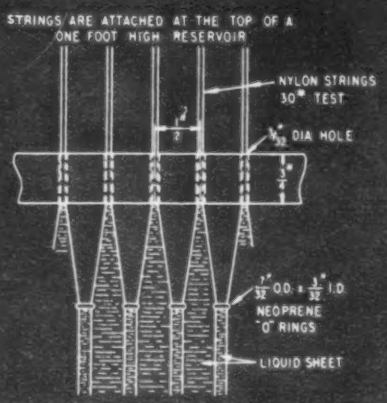
STRINGS ARE ATTACHED AT THE TOP OF A ONE FOOT HIGH RESERVOIR
NYLON STRINGS 30# TEST
1/32 DIA HOLE
3/4"
1/32" O.D. x 1/32" I.D. NEOPRENE "O" RINGS
LIQUID SHEET
STRINGS ARE ATTACHED AT THE BOTTOM OF A FOUR FOOT TALL FRAME AND ARE PULLED TO FOUR POUNDS TENSION

Fig. 4. Nylon string contactor.

WOOD and ARMSTRONG[83] on the transient response of a distillation column to changes in feed composition. The mathematical derivations contained therein follow the same approach as that given by WILKINSON and ARMSTRONG (1954), but simpler expressions result which are valid for the initial part of the response, and which can be extended to indicate the way in which a column approaches equilibrium.

Gas Absorption

Mass Transfer. Investigations in gas absorption mass transfer continue at a brisk pace with the production of good quality papers. The workers in this field are to be congratulated in that most data have been collected under circumstances akin to industrial operations. However, the study reported by TIMSON and DUNN[75] on the mechanism of gas absorption from bubbles under shear should not be overlooked. In this fundamental work the authors have determined the rate of mass transfer from bubbles sheared between a rotating drum and a stationary cylinder, and found that the absorption coefficient correlated in terms of the penetration theory agreed well with experiment. They also found that surface-active agents reduced the absorption rate, suggesting that this was due to inhibition of circulation on the bubble surface.

The other publications on gas absorption mass transfer present relationships for evaluation of the absorption coefficient on packings. Thus SALAMON'S[65] relation is based on SHERWOOD and HOLLOWAY'S data (1938), and assumes that the absorption coefficient is a function of the square root of the Schmidt number. A similar study on an unusual system has been reported by WARNER,[79] who absorbed zinc vapour from its mixture with nitrogen in molten lead flowing over steel Raschig rings. The author was interested in studying mass transfer under conditions where the irrigating liquid did not wet the packing. He compared this system with the ammonia water system, and was able to show that conventional gas absorption theories apply under non-wetting conditions.

Finally, reference should be made to CORNELL,[14] who reviewed the published data for heights of transfer unit (H.T.U.) and has presented new data on commercial-size towers.

Absorption Tower Hydrodynamics. A very fundamental study of this aspect of absorption is the paper by SIEMES and BORCHERS,[70] who photographed bubble swarms at different heights above a gas distributor. They found from frequency curves that the distribution of bubble sizes had a single peak. The distribution curve was characterized by a mean diameter and a standard deviation. Bubble sizes are discussed in terms of distributor aperture, gas flow rate and height of bubble above the distributor.

Another paper of high quality is that presented by CAIRNS and PRAUSNITZ,[12] who studied longitudinal mixing in packed beds at liquid flow rates ranging from Reynolds numbers of 3 to 4500. They injected salt solution through a simulated plane source and found that when the injections followed a step function Einstein's model was applicable. The results are expressed in terms of eddy diffusivities as a function of hydraulic radius.

The remaining papers on this aspect of absorption towers deals with pressure drop, loadability, hold-up and distribution of gas and liquid. Many workers continue to study ring-type packings, as, for example, DAVIES,[15] who publishes a nomogram to give the pressure drop across wet drained Raschig rings in terms of the ring diameter and pressure drop across the dry packing. However, an improved correlation of pressure across wet packings has been proposed by EDULJEE,[19] who combined the well-known LEVA (1954) correlation with that of OTAKE and KIMURA (1953). When the improved correlation was tested on experimental data of KIRSCHBAUM and DAVID (1953) for distillation of organics, the mean deviation was 18 per cent, which is good if one considers the difficulty of predicting physical properties under the conditions of testing the correlation. WHITT[81] too studied gas and liquid flows over ring packings. He concluded that gas flow is mostly on the outside of small rings and equally distributed for rings greater than 2 in. diameter. Liquid flow is mostly equally distributed over small rings with a tendency to flow inside large rings. The consequent effect on mass transfer is obvious.

BILLETT[9] studied the loading and flooding characteristics of the newer types of packing, including solid helices and wire gauze packing. He was able to propose a relation for calculating the permissible vapour velocity when the liquid passed over the packing as a film. The equation is based on the Nusselt skin-film theory and experimental and practical results agreed quite well.

Finally, liquid hold-up and pressure drop was also studied by WARNER[80] under conditions where the irrigant did not wet the packing. He used mercury for the liquid and hydrogen and nitrogen for the gas phase. A correlation was proposed which is claimed to be suitable for high-temperature molten metal systems.

New Packings. Two new tower packings have been described in the period under consideration. The first, proposed by HASELDEN *et al.*,[31] has been called "overflow packing", and essentially consists of a corrugated metal sheet containing rows of rectangular metal holes punched near the apices of the corrugation. It has been developed for insertion in a fractionating condenser as used on liquid air plants, but the characteristics make it very suitable for absorption and distillation tower packing. The other packing is suitable for situations where corrosion risk is high. It is reported by HILLIARD[35] and consists of graphite sections assembled into a polybloc construction. This author gives an account of the design and construction of polybloc absorbers and also reports the performance data of a unit absorbing hydrogen chloride in water.

Gas Absorption and Chemical Reaction. This aspect of mass transfer is receiving more and more attention, and it is pleasing to report that design techniques are now being proposed that consider the chemical reaction rate.

Since HATTA (1929) first published his analysis of the absorption of carbon dioxide in caustic alkali, many theoretical papers have been published extending his theory to account for other types of reactions, and during the past year ORLANDER[57] has extended the analysis to account for equilibrium reactions. However, ORLANDER'S analyses include an analysis by the penetration mass transfer model in addition to the film theory. A somewhat similar analysis, taking into account heat transfer in addition to chemical reaction, has been put forward by SPALDING.[71] The method has an aerodynamic basis and is of general applicability.

A bridge between the purely theoretical paper and the equipment design type of paper is the very lengthy article by TELLER.[74] The information is not new and the article is more for student consumption.

Two excellent papers dealing with the design of equipment to carry out simultaneous gas absorption and chemical reaction processes are those of ELLIS[20] and KING and FIELDING.[43] ELLIS has utilized VAN KREVELEN'S graphical technique (1954) to correlate absorption rates of carbon dioxide into potassium carbonate and monoethanelamine solutions. The analysis for the second-order reaction of carbon dioxide is almost identical with VAN KREVELEN'S, but for the suspected third-order reaction between the carbon dioxide and the amine a new parameter r_{3C} has been proposed which results in a reasonable correlation.

KING and FIELDING'S paper presents the stagewise analysis of nitric oxide absorption in water. The method put forward is a modification of the MCCABE-THIELE construction, and depends upon the selection of suitable molecular species

for solute, solvent and carrier gas. If this could be done for other similar systems the method would be of general application.

A new approach to this topic has been made by DODDS *et al.*,[17] who has shown that co-current absorption is advantageous in the case of absorption with fast chemical reaction, because under such operating conditions the mass transfer coefficient will be higher. That is when the driving force is low.

Finally, a new apparatus suitable for experimental investigations of gas absorption with simultaneous chemical reaction has been described by BROMLEY *et al.*[11] The apparatus consists of taut nylon strings 0.25 inches apart and arranged on a $3 \times 1\frac{1}{2}$ in. base, with the strings 4 ft long. The column so formed is easily wetted, giving dynamic liquid sheets. The author describes the experimental technique he followed in studying the absorption of carbon dioxide in ammonia liquor when high mass transfer rates were obtained at high throughput and low pressure drop.

Gas Absorption Processes. During the period being considered, three interesting absorption processes have appeared in the literature. The first, by BENSON and FIELDS,[5] discusses the scale-up of the hot potassium carbonate process for the removal of CO_2 and H_2S from ammonia synthesis gas and from various gaseous fuels. Regeneration efficiency of five commercial plants is compared to pilot-plant data. Regeneration is also the theme of BHARGAVA'S[7] paper describing the steam stripping of carbon dioxide from soda lye solutions. He discusses the effect of inlet lye and steam rates on the stripping operation performed in a bubble-cap plate.

PIESTER[63] gives an account of the design of a commercial unit to desorb hydrogen sulphide from brine. The basis of the design was experimental mass transfer data, and it was found that the commercial unit's performance came very close to the designed performance. The author suggests that the error was probably due to incorrect scale-up of the packing.

Liquid Extraction

Phase Equilibria is an important aspect of liquid extraction studies and continues to receive a lot of attention from workers in this field. Hence, during the period under review many publications of liquid equilibria have appeared. These cannot be discussed, but any reader interested in a particular system can consult the reference cited in the list below:

Ternary Systems

(a) Neptuneum—plutonium, and organonitrogen or organophosphorus compounds ... ... (82)
(b) Lead nitrate—nitric acid—water ... ... (24)
(c) Normalheptane—cyclohexane—aniline ... (40)
(d) Ammonia—phosphoric acid—water ... ... (65)
(e) Acetic acid—furfural—water ... ... (33)
(f) Perfluoroheptane—perfluorocyclic oxide and normalheptane or carbon tetrachloride ... (47)
(g) Toluene—methylcyclohexane and perfluoroctaneate ... ... (47)

Quadruple Systems

Water, benzene, triethylene glycol and dimethyl ether ... ... (56)
Acetic acid, formic acid, chloroform, water ... (61)
Acetic acid, propionic acid, furfural, water ... (34)

Binary Systems have been summarized by JACKSON and DRURY,[38] who report 1600 observations of miscibility. It is well known that most miscibilities can be predicted, but most of the systems reported are exceptions.

The prediction of equilibrium tie-lines is a most important point in liquid extraction stagewise analysis and many techniques have been suggested; e.g., OTHMER and TOBIAS (1942) and HAND (1930). However, HERIC and RUTLEDGE[33] have proposed a graphical procedure based on the lever-rule principle which the authors claim is satisfactory when analysis of the phases is unavailable. Accurate results are shown for the examples quoted, but because of the exceptions to the above prediction techniques it would be interesting to know the limitation of this new procedure.

Stagewise Analysis. Three interesting publications on this aspect have appeared during the period. The first, by BLUMBERG,[10] extends the McCabe-Theile stepwise procedure to partially miscible systems. The method is rapid but cannot be as accurate as the Ponchon method. The second paper by ELLIS[19] is of a somewhat specialized nature in that the author refers to "extraction sites" in the solvent, thus comparing dissolution with adsorption on a solid. The method again finally depends on a McCabe-Thiele type of diagram.

The final paper by ARIS[2] deals with cross flow extraction. Here the author applies the concepts of dynamic programming to the allocation of the quantity of a solvent to each stage of a cross flow process in order to determine the optimum solvent quantity for a given extraction. The analysis is illustrated by an example.

Equipment. Most of the reports on solvent extraction equipment refer to the mixer-settler extractor. However, some papers have been published on other types of apparatus. Thus WOODLE and VILBRANDT[64] investigated the effects of ultrasonic insonation on extraction rates of a spray tower. They stated that the increased rate was due to increased interfacial area, removal of stagnant layers at the interface, and increased circulation within the droplets. KARR[41] also studied the effect of pulsations on the rate of extraction. He found that the H.E.T.S. was substantially independent of the throughput up to flooding but depended only on the pulsation rate. Therefore, the author proposes that scale-up should be straightforward.

The remaining papers reviewed dealt with mixer-settler extractors and the most fundamental of those considered was one by BARKER and TREYBAL.[3] These authors studied the rate of dissolution of particles of boric acid, rock salt and benzoic acid in water in an agitated tank, with the object of studying the mass transfer coefficient of the continuous phase surrounding dispersed particles. They found that the mass transfer coefficient was independent of the particle size and the Schmidt number, but it could be expressed empirically as a function of the volume of the mixing vessel and the Reynolds number expressed in terms of the agitator diameter. The results are claimed to be useful in the design of extraction mixers. TREYBAL[77] has also made a further contribution to the design of mixer-settlers during the period under review. In this particular paper he established relationships which enable the most economic values to be assigned to the major variables of the extraction process. The variables include solvent feed rates, solute in recycled solvent and rejected raffinate. The relationships proposed can also be used to scale-up mixer-settlers from laboratory data and in this respect TREYBAL'S paper is somewhat similar to RYON *et al.*[66] which considers scale-up of mixers and settlers on the basis of geometrical similarity. RYON'S basis of mixer scale-up is power input per unit volume, which the reviewer feels is an oversimplification. Settlers are designed on the basis of flow rate per unit cross-section, but this view conflicts with the proposals of LOWRY and WILLIAMS (1958), who state that the heterogeneous wedge length is the best basis.

The economic design has also been discussed by QUALLINE JR.,[62] who suggests that optimum design depends on close attention to the balancing of total cost of the solvent recovery against the value of the solvent lost.

Finally, FENSKE[23] has reviewed the state of solvent extraction in oil refineries.

The references to this article appear on page 326.

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ADSORPTION PROCESSES

After indicating the extensive interest that has now developed in adsorption, this review lists applications of adsorption techniques for process separation purposes. These include the recently developed molecular sieves and permeable membranes, in addition to fixed, moving and fluidized beds. Also, correlations of experimental data and theoretical papers are briefly discussed

by J. W. CARTER

THE interface between two phases is a region of special interest to chemical engineers because of its importance in controlling transfer processes. The usually continuous nature of processes such as distillation, absorption and liquid-liquid extraction has contributed to their development as unit operations. Thus transfer mechanisms can be approximated in the form of coefficients whose variations with the important parameters can be determined experimentally, forming a basis for plant design. In the case of adsorption plant design, the normally unsteady state operation has not helped in the analysis, but in many instances adoptions of methods used for the previously mentioned liquid-vapour separation processes have been suggested.

An immense amount of information has been published in the last ten to fifteen years on adsorption phenomena. The larger proportion is concerned with the physical chemistry of this subject and at present little of it adds up to an interconnected theory. It is the intention of this review to include certain chemical engineering applications of adsorption which are used for separation processes. As background to this, however, it is worth while knowing something about the intense post-war interest that has developed in fundamental phenomena and also certain developments of industrial importance.

The amount and range of recent fundamental work is best shown by the publication of the *Second International Congress of Surface Activity (1957)*,[1] volume II of which deals with solid/gas interfaces, and the tenth Symposium of the Colston Research Society[2] on the structure and properties of porous materials. In the former, as might be expected, the larger proportion of the papers are concerned with the properties and characteristics of solid surfaces and include ones on the pore structures of aluminas and silica gels by BOER and KISELEV respectively. DERJAGUIN proposes a corrected form of the capillary condensation equation, showing its use for determining pore structure from adsorption and desorption isotherms, while the papers by OLIVIER *et al.* and JOY are concerned with surface properties and their effects on interaction of adsorbate molecules with the solid surface. Hysteresis is also of wide interest and ARNELL discusses its occurrence both in rigid and non-rigid adsorbents. The two papers by QUINN and MCINTOSH and FLOOD and LAKHANPAL are particularly interesting in their correlations of the very small dimensional changes of porous glass and carbon rod adsorbents, especially when hysteresis occurs. Other papers by AMBERG *et al.* and KISELEV are thermodynamic studies of adsorption hysteresis. It is also worth noting the new and interesting experimental techniques used in some of the investigations on the state of the adsorbed molecules reported in this symposium. Measurement of the shifts in proton magnetic resonance frequencies of organic compounds adsorbed on carbon by GRAHAM shows the thickness of the film which is affected by surface forces. Also, the discovery of new absorption bands by YATES and SHEPPARD in the infra-red spectra of hydrocarbon vapours on porous glass enables the effect of surface forces on orientation to be determined, while another paper by DERJAGUIN discusses the formation of

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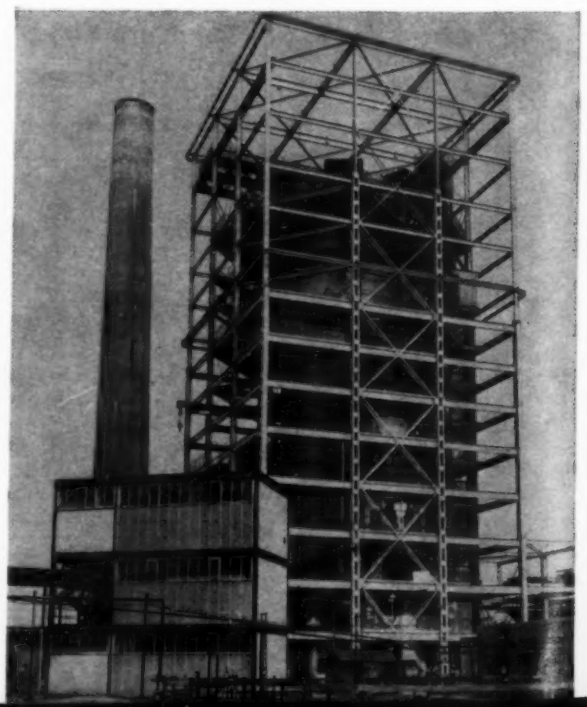


Fig. 1. Plant for the recovery of carbon bisulphide by means of a fluid bed of activated carbon.

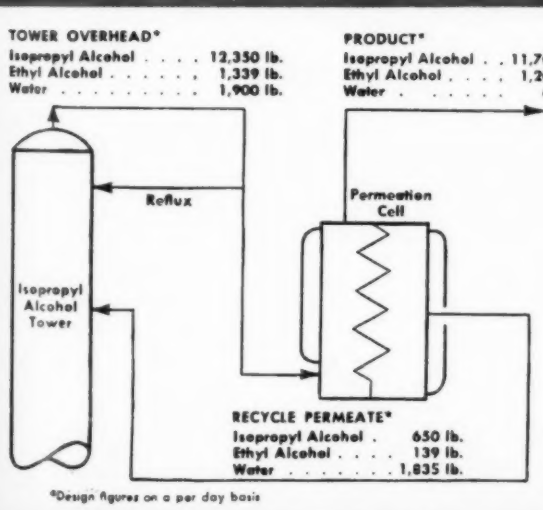
(Courtesy Courtaulds Ltd.)

adsorption films on a smooth glass surface, for the study of which he used an optical micropolarization method.

A further paper by KISELEV on the structure of corpuscular adsorbents such as the silica gels and its influence on their properties and one by BOER on hysteresis loops and shapes of capillaries are contained in the Colston Research Papers. Also, contributions by FOSTER *et al.* and MOUGEY give details of different methods of preparing silica gels and discuss their effect on adsorptive properties and structure. Extremely interesting and informative papers on the surface characteristics of carbons and crystalline adsorbents are included by WYNNE-JONES and KINGTON, both being concerned with the effect of surface heterogeneity on adsorption. It is perhaps invidious to make such a selection from the wealth of papers in these symposia, but at least it does indicate the type of work done and may stimulate further interest on the part of the reader. The mention of selected papers from those presented at the Second International Congress on Catalysis,[3] held this year in Paris, may appear less relevant. However, although in the study of heterogeneous catalysis chemisorption is of major importance, the interest in such things as pore structure and surface properties stimulates physical adsorption investigations. This Congress has many papers on this theme and two of them are of particular interest. The first, by SCHOLTEN and ZWIETERING, shows the oxidation of nitric oxide over silica to be an example of physical catalysis. The acceleration of the reaction caused by the silica is a result only of the increased concentration of the reactants by physical adsorption and it is thought that other reactions, for example, the hydrolysis of phosgene by water adsorbed on activated charcoal, may be accelerated for the same reason. The other, a study of the dehydration of Vycor glass using infra-red spectroscopy by LITTLE and MATHIEU, shows the importance of the presence of surface hydroxyl groups for adsorptive properties in this type of adsorbent, as did KISELEV[1] for silica gels.

The use of adsorption for industrial separations has primarily been concerned with fixed and moving bed operation as occurs in solvent recovery, gas drying and the separation of hydrocarbon mixtures in the vapour and liquid phases. Recently published literature is by no means as abundant on these aspects as the more fundamental ones. However, there are two developments which are extending considerably the use of adsorption techniques. These are the introduction of synthetic molecular sieves and adsorptive membranes. The synthetic molecular sieves are a development resulting from BARRER'S earlier work on natural zeolites. These sieves are porous crystalline adsorbents, possessing an open alumina-silicate framework. The sieving properties arise from the dimensions of the windows in the cages through which an adsorbate molecule has to pass before adsorption occurs in the cavity beyond. The lattice is anionic and in addition to the Si-O-Al bond distances its dimensions and sieving properties also depend upon the cation present such as Na and Ba, or organic ones in the case of the layer-lattice sieves developed from bentonites, in addition to the crystal structure. BARRER[4] classes the sieves in five groups by their ability, or otherwise, to adsorb a range of molecules of increasing molecular dimensions. Synthetic zeolites are available in the form of pellets and are most often used in fixed beds. Their widest use so far is in the petroleum industry for hydrocarbon separation —for example, occlusion of n-paraffins from mixtures with branched chain ones—and there are many publications[4–8, 37] describing these and other uses, including the various methods available for desorption. These other uses include the separation of incondensible gases at low temperatures where appreciable adsorption occurs and is of potential use, for example, in the recovery of the small amounts of rare gases in a pure state in the air separation process. Also, a whole series of organic liquid mixtures can be resolved by total, or almost total occlusion of one component in preference to the others. Further, the very high affinity of these heterionic adsorbents for polar molecules such as water has meant their wide use for intensive drying of gases and organic liquids. More fundamental papers[1, 2, 9] discuss the structure of molecular sieves, rates of adsorption and equilibria, one by BARRER[2] comparing their properties with other porous crystals which act as host lattices, such as the urea/n-paraffin and thiourea/hydrocarbon adducts, also used for separation purposes.

Separation of gases with different molecular weights by molecular diffusion in capillaries or porous material is well known; for example, the separation of the isotopes of uranium as their hexafluorides. When strong adsorption of one or more components of a mixture occurs in the porous medium the rates of diffusion are not predicted by the kinetic theory of gases. Using a Vycor glass micropórous diffusion membrane, KAMMERMEYER[10] has separated a large number of binary mixtures, mainly azeotropes, by selective permeation in the vapour


TOWER OVERHEAD*
Isopropyl Alcohol . . . . 12,350 lb.
Ethyl Alcohol . . . . . 1,339 lb.
Water . . . . . 1,900 lb.
PRODUCT*
Isopropyl Alcohol . . 11,700 lb.
Ethyl Alcohol . . . . 1,200 lb.
Water . . . . . 65 lb.
Reflux
Permeation Cell
Isopropyl Alcohol Tower
RECYCLE PERMEATE*
Isopropyl Alcohol . 650 lb.
Ethyl Alcohol . . . . 139 lb.
Water . . . . . 1,835 lb.
*Design figures on a per day basis

	MEMBRANE PERMEATION	HEXANE AZEOTROPING
INVESTMENT FOR NEW EQUIPMENT	$76,000	$100,000
OPERATING COSTS PER YEAR*		
• Labour	6,570	6,570
• Supervision	990	990
• Maintenance labour	1,900	2,500
• Labour benefits	1,890	2,010
• Maintenance materials	1,140	1,500
• Hexane loss	—	470
• Membrane replacement	220	—
• Utilities	740	1,620
• General and administrative overhead	6,240	6,760
• Property taxes and insurance	1,140	1,500
CAPITAL COSTS†	$23,400	$30,800
UNIT COST, CENTS/LB.‡	1.36	1.68

*Based on operating time of 85%.
‡Based on 10,470 lb/stream day of crude isopropyl alcohol feed (dry basis).
†Based on new equipment cost of $76,000 for permeation, $100,000 for azeotroping, five-year payout, 10% per year depreciation, 52% income tax

Fig. 2. An economical process for the upgrading of the tertiary azeotrope of isopropanol-ethanol-water. It is superior in this respect to extractive distillation using hexane as the entrainer.

phase, and although no commercial scale application is yet reported, the usefulness of this technique is obvious. Amongst the many papers[10–18] on membrane permeation, the use of polymeric membranes appears to show considerable promise in the separations of such systems as mixtures of M.E.K., i-propanol or ethanol with water.[15] Other separations are also included, and one technique involves contacting one side of the membrane with the liquid mixture and drawing off the enriched vapour at the other.

Permeability values of polyethylene, polyvinyl chloride, polyvinyl acetate and cellulose acetate membranes are given by KAMMERMEYER in the Twenty-fourth Chemical Engineering Progress Symposium.[18] This Symposium not only discusses membrane permeation, but also includes papers on separation by adsorption, dialysis and ion exchange. As the first serious attempt to link the similarities of these three fields, it can be expected to stimulate interest in and application of adsorption and related processes.

Fluid-solid Transfer Operations

The unique properties of molecular sieves offer many separations hitherto difficult or impossible by adsorption methods. They will, however, normally be adapted by means of the previously developed techniques of solid-fluid contacting which have been used for other adsorbents. These techniques will be summarized from the point of view of single-component recovery and multi-component separation. To present a reasonably comprehensive picture it has been considered desirable on this occasion to include earlier references than would be normal in a review of this sort.

Fixed Beds—Single-component Removal

The most widely used technique for the removal of one component employs fixed beds in a cyclic process of adsorption and regeneration. There are many descriptive papers[19–24] which, though perhaps making no significant contribution towards design and operation, nevertheless are useful in outlining the systems that are available and separations that can be carried out. Those using molecular sieves[4–8, 37] have already been mentioned and, of the others, chapter 12 of KOHL and RIESENFELD[24] is a useful introduction to adsorption for gas purification. Other references include the operation of adsorptive drying plant,[25] carbon dioxide removal,[26] solvent recovery systems,[22] including costs and comparisons with absorption and cooling for gas drying applications,[21] and gaseous and liquid hydrocarbon dehydration.[20] In other instances, the publications are no more than an introduction to adsorption processes.[19, 23]

It is interesting to note the lack of published experimental data on the adsorption of vapours, other than water in fixed beds, and those available, namely NO_2 adsorbed on silica gel[27] and CS_2 on charcoal,[28] are relatively old and refer to work on beds 1 or 2 in. in diameter. Those of water vapour adsorption on silica gel,[29–34] activated alumina,[33–36] molecular sieves[37] and drierite[38] include small-scale tests under both isothermal and adiabatic conditions and large-scale ones with the results of tests on industrial installations.

Analytical Correlations of Experimental Results

Of these workers who have analysed their results, EAGLETON's adsorption of water vapour by silica gel is one of the earliest,[33, 39] and in addition to the gas film resistance in the boundary layer round the granules also uses a solid-film resistance in series with it to represent transfer in the adsorbed phase in the granules themselves. These give reasonable prediction of his curves, although it is admitted that the accuracy of the solid-film mass transfer coefficients is not high.

The use of a solid film coefficient to represent mass transfer in a spherical granule is, of course, itself an approximation, and JURY and LICHT[38] use instead a simplification of the series due to WICKE representing diffusion into a sphere. This is done by approximating the series to the first term, and equations are produced predicting outlet concentrations for the alternative cases of diffusion in the granules or through the boundary layer controlling. The experimental results, adsorbing water vapour on drierite, correlate best for the latter case, but the peculiar shape of the outlet concentration curve at the start of the runs suggests shortcomings in the experimental technique, most likely the regeneration procedure. VREEDENBERG's[28] mass transfer equations are based on a Langmuir form of rate equation and the solution is similar to that dependent on gas phase resistance only as was first proposed by HOUGEN and MARSHALL.[40] The results VREEDENBERG obtained in adsorbing carbon disulphide from air by activated charcoal show quite good agreement with calculated curves and are based on isothermal operation as in the case of EAGLETON's and JURY and LICHT's experiments. ALLANDER's publication[31] on moisture vapour adsorption in silica gel beds takes into account the temperature rises occurring during adiabatic operation. The first part of his experimental work studied adsorption by a single granule and showed that a good degree of approximation is obtained by considering that the amount of heat used in raising the adsorbent temperature is negligible when adsorption times are not brief. Under these conditions it is to be expected that the gas film resistance controls mass transfer and the equation for outlet concentration is based on this premise, its validity being confirmed by tests on commercial adsorption equipment.

SANLAVILLE[36] also takes into account the effect of temperature rise due to the heat of adsorption in drying air with activated alumina. His assumption that heat transfer is controlling for the conditions of his experiments, and that water vapour adsorption is in equilibrium, is reasonably justified by the agreement between calculated and experimental values of air temperature and water vapour concentration.

Empirical Correlations of Experimental Results

The correlations of the above authors are quite useful for prediction and design purposes as long as their limitations with respect to heat and mass transfer are appreciated. Other authors who analyse their experimental results use empirical forms of correlation which are undoubtedly more useful and easier to use within the restrictions of the conditions investigated. FOSTER and DANIELS[27] correlate the effects of silica gel depth, temperature, particle size, gas velocity and rates of adsorption for nitrogen peroxide and water vapour, in terms of the average saturation of the gel bed and the average adsorption efficiency during the run. However, they do show how the h.t.u. can be calculated and suggest that, particularly in the case of NO_2, the assumption of gas film resistance controlling is incorrect in view of the strong interdependence between rate and adsorptive capacity. RATHMELL and BATEMAN[34] for atmospheric air dried in pilot-plant scale beds of activated alumina or silica gel, correlate contact time against the ratio of inlet humidity to mean bed capacity with inlet humidity and breakpoint time as parameters. This is done for specific breakpoint humidity values and covers a very useful range of inlet concentrations, flow rates and particle sizes. The use of contact time must, however, be interpreted carefully, since this is only a function of the total amount of adsorbent and air flow rate. A different shape of bed, whilst giving the same contact time, would alter the interstitial velocity, the different gas film coefficient thus changing the mass transfer characteristics and also the shape of the outlet concentration curve.

The analysis method of predicting the behaviour of solid adsorbents, described by ROSS and MCLAUGHLIN,[29] uses the properties of partial differentials to determine the variation

of a dependent property such as adsorptive capacity as a function of such variables as inlet humidity, temperature, velocity and bed depth.

$$\text{Thus } X = f(Y_1, Y_2, \ldots Y_n)$$
$$\text{and } dX = (\partial X/\partial Y_1)dY_1 + (\partial X/\partial Y_2)dY_2 + \ldots (\partial X/\partial Y_n)dY_n$$

where X and Y are the dependent and independent variables respectively. These authors obtain empirical equations for adsorptive capacity, efficiency and regeneration time, in terms of what are considered to be the important variables, from their experiments on water vapour adsorption from air by silica gel. However, the variables themselves are very much interdependent; for example, the bed temperature is a function of not only the inlet temperature but also inlet humidity and flow rate, in addition to the gas and adsorbent properties. Thus, although this method might appear useful to obtain design formulæ without reference to the mechanisms involved in the process, the accuracy of these formulæ will fall rapidly when used for conditions substantially different from the experimental ones.

LUIBIMOV and SMIRNOV's[32] use of dimensionless groups to express their results of vapour adsorption in activated carbon and silica gel is perhaps not quite as restricted as Ross and McLaughlin's method, although it is by no means of general validity. The correlation obtained is given as:

$$Ki = \mathrm{Re} \,.\, \mathrm{Pr} \,.\, C_n \,.\, \Gamma$$

where Ki = the Kirpichev diffusion criterion = $\beta d^2/D$ (dimensionless);
β = mass transfer coefficient;
d = bed diameter;
D = diffusion coefficient of vapour in gas;
Re = Reynolds number based on d;
Pr = Prandtl number;
C_n = ratio of inlet vapour concentration to mean driving force in gas phase;
$\Gamma = d/h$ = bed diameter/bed height.

It is difficult to understand why granule diameter is not also important, in fact more so than the bed diameter, since the work was done on different granule sizes from 1.5 to 2.5 mm. Also, any value the correlation has for the particular adsorbents used is restricted to operating conditions in which mass transfer in the gas film controls, since it does not take into account transport in the solid. The last of the empirical correlations, that of MILLER and ROBERTS[35] for water vapour adsorption by alumina beds, does no more than attempt to assess the effect of relative humidity on the average adsorption capacity. In addition to data on isothermal and non-isothermal systems, results from industrial-scale plant are included. However, there are many unknowns not investigated, so that the information is of quite limited use in its present form.

Theoretical Work

Of the papers dealing essentially with theoretical aspects of adsorption in fixed beds, those of AMUNDSON,[41–45] GOLDSTEIN,[46, 47] VERMEULEN[48, 56] and their co-workers and ROSEN[49, 50] are the most rigorous. These contributions include the effects of solid phase diffusional resistance, in addition to that of the boundary layer, but, except in one instance, the solutions are not easily applicable to experimental data. This exception is provided by ROSEN,[50] whose dimensionless film resistance, bed length and contact time groups may be used with tabulated values, or curves, to predict an outlet concentration curve with steady inlet conditions. This was used by the author[25] to predict outlet concentration curves for both isothermal and adiabatic adsorption in silica gel and activated alumina beds. The agreement with the experimental curves was quite good and a considerable improvement on previous methods proposed by HOUGEN and MARSHALL[40] and MICHAELS.[51, 52]

The work of VERMEULEN and his fellow authors is best referred to in the most excellent contribution[48] in "Advances in Chemical Engineering", Vol. 2, entitled *Separation by Adsorption Methods*. The treatment of exchange processes is essentially for ion exchange systems and some of the circumstances, for example irreversible equilibrium, are not applicable to normal adsorption processes. However, VERMEULEN refers to THOMAS's general solution,[53] which he considers to be of the widest use for exchange processes in fixed beds giving outlet concentration in terms of an equilibrium factor, number of transfer units and a throughput ratio, all dimensionless, which has been worked out both in tabular and graphical form.[54, 55] The throughput ratio is a function of fluid throughput and bed dimensions, while the equilibrium factor for the case of adsorption is defined in terms of LANGMUIR's isotherm constant. The calculation of the n.t.u. depends upon the combination of fluid and solid film mass transfer coefficients, the latter, as previously mentioned, representing an approximation of diffusion into a spherical granule. However, it is demonstrated[56] that using a quadratic driving force of the form,

$$\text{rate of adsorption} = K\frac{(y^+)^2 - y^2}{2y}$$

K = a rate coefficient for the solid phase
y^+ = equilibrium concentration in solid phase
y = average instantaneous concentration in solid phase

gives a close fit with the diffusion equation over the whole concentration range, where internal solid phase diffusion is controlling. There are unfortunately no examples of the application of these equations and it is to be hoped that they will not be long coming.

It is usual to neglect the effect of longitudinal diffusion on the shape of the outlet concentration curve, and VERMEULEN[48] points out that only when fluid-particle equilibrium is closely approached does it become important and then may determine the shape of the breakthrough curve. The papers by LAPIDUS and AMUNDSON[43, 44] review the effect combined with external diffusion for a linear isotherm, and a later paper by ACRIVOS[57] proposes how it may be taken into account for non-linear isotherms in certain circumstances.

Of the other theoretical papers, that of most possible use is by REILLY[58] on unsteady state transfer in stationary packed beds. It is presented for heat transfer, but would be easily applicable to isothermal mass transfer. Its particular interest lies in the allowance of both arbitrary initial solid temperature distribution and also variation in inlet temperature. The solution applies for conditions under which the external fluid film controls the exchange process and is presented as Fourier integrals and series. Previous solutions[40, 53] of this type of problem are in the form of Bessel or other functions only tabulated for a limited range of the variables. The Fourier series solution converges rapidly, giving a good approximation, and may thus be a more useful form. The remaining papers include that of GLUECKAUF[59, 60] based on the theoretical plate concept for a linear isotherm. For more than three theoretical plates

$$\text{the ratio } \frac{\text{outlet concentration}}{\text{inlet concentration}} = \frac{C}{C_0} = \frac{1}{2}\left(1 - \mathrm{erf}\left[\sqrt{\frac{N}{\bar{v}v}}\,(\bar{v} - v)\right]\right)$$

where N = number of theoretical plates;
v = volume of fluid passed through at c;
$\bar{v}$ = volume of fluid passed through when $\frac{C}{C_0} = 0.5$;
erf $[x]$ = error function of x.

This concept is based on the assumption of equilibrium which is unlikely except at low flow rates and small granule sizes. Finally, BARRY[37] discusses what is termed the Mass

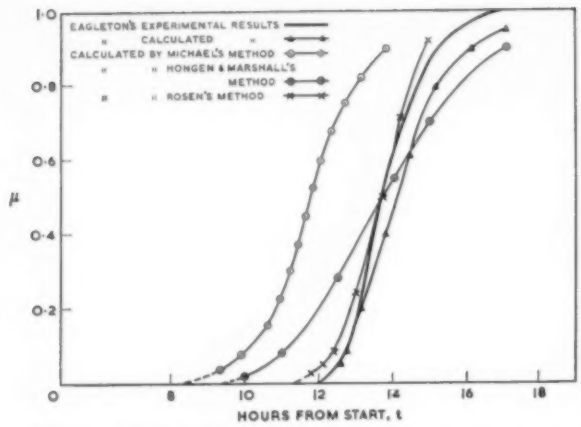


Fig. 3. Calculated break-through curve for MICHAELS' *method.*

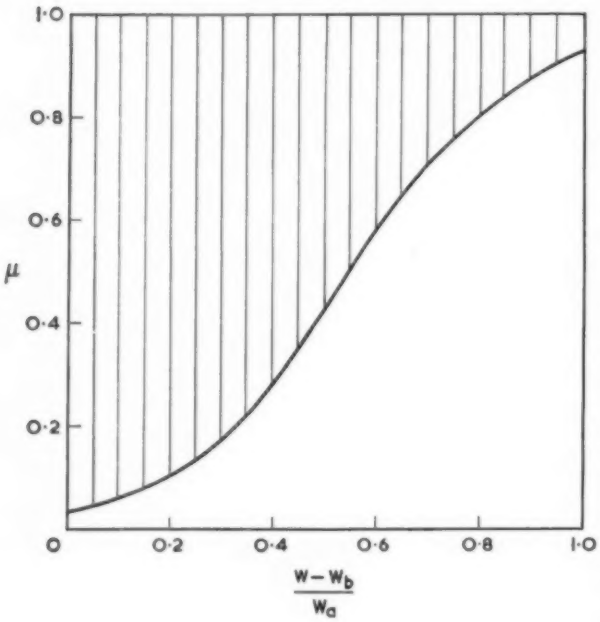


Fig. 4. Variation of outlet concentration with time. EAGLETON'S *run* S_2.

Transfer Zone approach, which would appear to be based on previous ideas of a constant width adsorption zone as proposed by MICHAELS[51] and others.[33, 48] This zone width would be determined experimentally as a function of flow rate and other variables, and so the proposal has no new contribution to make.

Moving and Fluidized Beds—Single-component Removal

The few publications about moving and fluidized beds for adsorption of single components is a reflection of their limited large-scale use. There are only three references to the applications of these techniques and include a novel 15 in. diameter countercurrent contactor with moving rabble arms for removing impurities from carbon tetrachloride down to 1 per cent of their inlet concentration,[61] an experimental unit with five 4 ft square trays with fluidized silica gel for drying large air flows for gas turbine research[62] and a plant for the recovery of carbon disulphide from the ventilating air in the viscose spinning process.[63] The latter equipment has a 38 ft diameter adsorber with five trays using fluidized activated charcoal. The drying plant removes over 80 per cent of the water vapour using gel depths on the trays of up to 6-8 in. and the charcoal plant recovers over 90 per cent of the solvent. Regeneration is carried out separately and in each instance consists of the application of heat plus a purge gas to help desorption. Steam coils are used for heating the adsorbent in the carbon tetrachloride and carbon disulphide plants, but the purge gases are air and steam respectively. In the drying plant, air heated by direct combustion of kerosene is drawn through the silica gel.

Published experimental data include desorption and adsorption of water vapour from air[62, 64, 65] on silica gel, carbon tetrachloride from nitrogen on activated charcoal,[66] iso-octane and toluene from air on alumina[67] and iodine as an impurity in carbon tetrachloride adsorbed on magnesium oxide.[61] COX[62] interprets his results of water vapour adsorption on silica gel beads as a mass transfer coefficient assuming complete mixing of the adsorbent and no back-mixing of the air flow. No systematic variation of this coefficient with air humidity or moisture content of the gel was found, but a significant increase with decreasing bed depth was observed. The explanation for this apparently illogical behaviour lies in the earlier work of HEERTJES and co-workers,[64, 65] who showed during desorption experiments of water from fluidized silica gel that mass and heat transfer from the air flow to the particles takes place in a very small depth—3 to 4 mm in their experiments—at the bottom of the bed. The work of RICHARDSON[67] and BAKHTIAR adsorbing toluene and iso-octane on 40-80 micron size alumina microspheres also confirms that virtually all the transfer occurs in a shallow zone above the bed support and that back-mixing of the gas is negligible. The high rate of approach to equilibrium in these experiments made it impossible to obtain values of transfer coefficients, but the results of HSU and MOLSTAD[66] adsorbing carbon tetrachloride on 20-60 mesh charcoal indicates that in the early stages of adsorption the process is gas film controlled and as the charcoal saturation increases, solid diffusion may take over. The case of combined gas phase and adsorbed phase resistances has been treated theoretically by KASTEN and AMUNDSON,[68] based on random movements of the fluidized particles, and for a linear isotherm gives the outlet concentration in the form of a rapidly converging series involving the important variables. This is quite straightforward to use, but has not been applied to any experimental results.

In addition, KASTEN and AMUNDSON[69] analysed theoretically the case of single-component adsorption in a moving bed, also allowing for both gas and adsorbed phase resistances. The solution again gives outlet concentration in the form of an infinite series and also graphs, but it has not been put to practical use. In his method of designing a continuous countercurrent adsorber, MOLYNEUX[61] applies the conventional use of operating and equilibrium lines from absorption practice to determine graphically the number of transfer units required to adsorb iodine from carbon tetrachloride on magnesium oxide. This approach is easy to understand and apply, but requires experimentally determined h.t.us for the system and operating conditions involved, which are not given in this paper.

Moving Beds — Multi-component Separation

A description of hypersorption was published some time ago[70] and subsequent contributions in the literature are few. The larger proportion of experimental work has been on equilibrium relationships, and these include vapour phase binary and tertiary mixtures of ethylene, ethane, propylene, propane, butene and iso-butane on silica gel and activated charcoal[71] and of methane, acetylene and carbon dioxide

on charcoal.[72] Other vapour phase data for binaries only on charcoal is given for combinations of ethylene, ethane, propylene, propane[73] and also ethanol, methyl-ethyl ketone, benzene, n-heptane, cyclohexane,[74] while liquid phase binary equilibria is published for binary mixtures of benzene, cyclohexane, toluene and i-octane on silica gel.[75, 76] The majority of these are correlated by the empirical relationship known as the capacity fraction equation,[71–74] other methods using data from the adsorption of single components based on adsorption potentials,[71, 72, 77] relative volatility[71, 72] and activity coefficients[78] not being very successful. For liquid phase adsorption a correlating equation by STUART and COULL[75] has been used to predict the benzene-cyclohexane data on silica gel. This equation involves the use of Van der Waals attraction constants calculated for mixtures and the concept of monomolecular adsorption, showing very good agreement with experimental results.[76]

With regard to rate data, both KAPFER[72] and CALDERBANK[73] found that from binary separations of hydrocarbon vapours in small-scale moving-bed charcoal columns, the resistance to mass transfer is essentially in the solid phase. CALDERBANK gives a mass transfer coefficient (hr^{-1}) as $K_s a = 6D/D_p^2$ approximately, where D = effective diffusivity and D_p = mean diameter of carbon granules, and KAPFER gives the h.t.u. based on gas phase concentration as $6\,G/L$ where G = gas flow rate and L = solids flow rate. Theoretical analyses of the operation of a hypersorption type separation process include that of GARNER and his co-workers,[74] using the capacity fraction relationship to calculate the curved operating line and thus determine the number of theoretical stages graphically, and also MOLE's proposals[79] for a unified theory for ideal separation processes such as distillation, absorption and adsorption. The latter involves the use of difference equations for each component, which can be solved by the transformation methods developed for distillation processes to derive the number of theoretical stages. Although examples of the use of the equations of GARNER and MOLE are given, they are not applied to any experimental data.

Membrane Permeation — Multi-component Separation

Data on this recent development, previously mentioned, was first published in 1954 by KAMMERMEYER,[10] when he gave details of the separation of eleven binary azeotropes composed from water, ethanol, methanol, iso and normal propanol, ethyl acetate, acetone, carbon tetrachloride, cyclohexane, benzene and carbon disulphide. The vapour of the azeotrope was forced through an adsorptive membrane of porous Vycor glass, pressure differences ranging from approximately 1 to 5 atm. In all cases the azeotrope was separated and in general the separation was in favour of the component with the lower critical pressure. Undoubtedly, the more strongly adsorbed vapour is the one which permeates most quickly as shown by subsequent papers on the separation of propane/carbon dioxide mixtures[12] by this method and adsorption equilibria for these two vapours[14] and also methanol and benzene.[13] Separation by adsorbed phase flow is complicated for porous Vycor glass by molecular flow in the vapour phase, since the mean pore diameter is approximately 60 Å, and this effect will be greater for higher pressure differences across the membrane. This may help or oppose the adsorptive separation, but is more likely to do the latter, since the faster diffusing molecules, those of lower molecular weight, are less likely to be the most strongly adsorbed. A further complication will occur if capillary condensation takes place, since molecular distillation of this condensate can again either assist or destroy the adsorptive separation. Neither of these complications are assessed by KAMMERMEYER and the prediction of permeation rates of the mixture by addition of the values for the separate components was unreliable, as might be expected. However, he does propose[18] a graphical method of determining the number of permeating stages required in a cascade to produce a given separation. This involves the use of an equilibrium diagram constructed by plotting the composition of the permeated gas against that of the unpermeated gas for isothermal conditions and a constant pressure difference across the membrane. Then, construction of the operating lines enables a McCabe-Thiele type diagram to be finally obtained.

KAMMERMEYER[18] points out that this graphical procedure can also be applied when plastic film barriers are used and gives permeability values for single vapours through film of such materials as polythene, polyvinylchloride, polyvinyl acetate and cellulose acetate butyrate. However, papers giving separations of industrial interest, namely water/isopropanol[15] and water/isopropanol/ethanol,[16] do not say what the membrane is composed of, but in each case the water permeates preferentially. Other separations, such as methyl ethyl ketone/water and ethanol/water, are detailed[16] with costs, based on pilot-plant data, the technique being to contact the upstream side of the membrane with the liquid mixture, drawing off a vapour downstream at a reduced pressure. It is interesting that in spite of the pumping costs due to the pressure differences across the membrane cells, combined with a definite life of several months for the membrane, it is claimed to be cheaper than extractive distillation in operating and capital costs in upgrading the tertiary azeotrope of isopropanol, ethanol and water. Using Vycor glass, KAMMERMEYER has compared six of his earlier azeotropic separations[10] in the vapour phase with separations having liquid phase both upstream and downstream of the membrane.[17] Not only are the flow rates lower, but the same component as in the vapour phase is not the more permeable one in every case. The latter is ascribed to solubility effects not present in the vapour phase, and it is obvious that in spite of their novel and useful separations the wider application of membrane separation techniques is at present restricted by pressure drop requirements to produce useful flow rates and also lack of knowledge enabling the effect of process variables to be predicted.

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New Organic Chemicals Manufacturing Plant

A MAJOR advance in nickel-plating systems in the last few years has been the rapidly expanding use of organic brighteners for producing a bright electrodeposit without the laborious polishing that is required with conventional matt nickel deposits. The organic chemicals used in the Efco-Udylite nickel brighteners manufactured and sold by the Electro-Chemical Engineering Co. Ltd. are highly specialised materials and are not available on the open market. Therefore, to ensure adequate supplies of brighteners manufactured under strict quality control, Electro-Chemical Engineering have built and placed into operation at their Woking factory a complete manufacturing plant for the production of raw materials for six of their nickel brighteners.

The majority of the plant is used for the manufacture of the constituents of brighteners 41 and 61 which are used in the highly successful Efco-Udylite 66 bright nickel process. The equipment in this plant consists of a number of stainless-steel steam-jacketed reaction vessels, rubber-lined purification tanks and rubber-lined intermediate and bulk storage tanks: the interconnecting pipework is also rubber lined. The brighteners are manufactured in batches from readily available raw materials in the stainless-steel reaction vessels which are fitted with glass condensers for reflux distillation operations. On completion of the reaction, the crude products pass into the rubber-lined purification tanks where they are treated, purified and then filtered to the intermediate storage tanks. The brighteners are then held in the intermediate storage tanks until they have been approved by laboratory analysis and plating tests, after which they are pumped to 8000-gal bulk storage tanks. When required, they are then pumped to further storage tanks from where they are dispensed into containers for despatch to customers. The use of stainless-steel and rubber-lined equipment in the various process stages has been found essential in order to maintain product quality and to resist corrosion of the equipment.

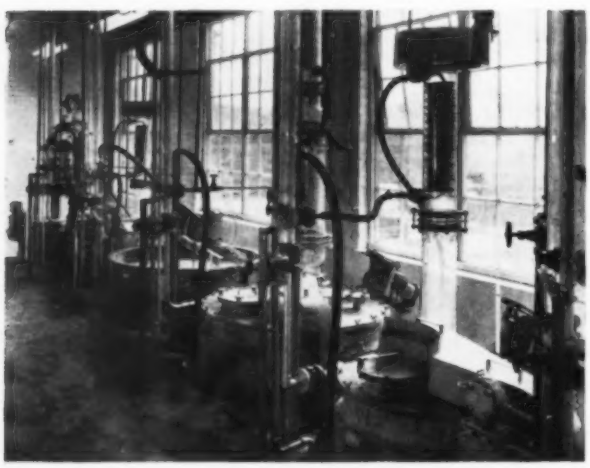

Fig. 1. Stainless-steel reaction vessels and glass condensers.

The plant is housed in a new building designed by Campbell Gifford & Morton Ltd., who were the consulting engineers for the whole project. The building, attached to the main factory, is constructed of brick and has acid-resistant flooring, while the internal walls are glazed to a height of 8 ft. A comprehensive fume extraction system has been installed and removes noxious fumes from the tops of all condensers, vessel openings and purification tanks. As inflammable raw materials are used, all the electrical equipment and fittings are of a flameproof type.

By the careful choice of plant, therefore, and by having manufacturing arrangements situated within the Electro-Chemical Engineering organization, close production control over the purity of these nickel-plating solution brighteners and reliable deliveries of the brighteners to customers have been achieved.

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APPLIED REACTION KINETICS AND REACTOR DESIGN

The history of industrial kinetics is briefly traced up to the time of the introduction of van Krevelen's concepts of macro and micro kinetics. Mass transfer theories, including the surface renewal and turbulent boundary layer theories, are discussed together with the effect of such parameters affecting reactors as space velocity, hold-up time and residence time distribution. The design is considered of a number of types of reactor, including homogeneous, heterogeneous, stirred tank, tower and fluidized-bed reactors. Completely rational design procedures for fluid-bed reactors are not possible unless residence time distribution data are available and the degree of backmixing evaluated. The author reviews, in conclusion, a number of design methods, including one making use of an equivalent temperature to account for actual temperature variations within a reactor, and another which makes use of the "height of a reactor" concept

by L. K. DORAISWAMY

THE object of applied reaction kinetics is to bring together chemical kinetics and physical phenomena so that one may carry out a given class of reactions in a single kind of reactor. The trend towards this generalized approach to reactor design is no doubt increasing, but the direction that was given to it in the early stages of development has now diffused into several channels of basic physico-chemical investigations which must be sifted and correlated before their applicability to reactor scale-up can be assessed. In this paper the progress of applied kinetics will be surveyed since the time it was recognized as a necessary area of work in chemical engineering. It is not possible to deal at length with the different aspects of the subject, but it is hoped that the material presented will provide an integrated picture of the present status of chemical reactor development.

Historical Development

The earliest recorded investigations in the field of reaction kinetics were carried out over 200 years ago[193] in the Freiburg Foundries of Saxony and were concerned with the effect of acid concentration on the rates of dissolution of zinc and copper metals in acid solutions, but the first paper on industrial kinetics did not appear till 1923 when LEWIS and RIES[123] published their results on the kinetics of the catalytic oxidation of sulphur dioxide. This was followed by the work of BENTON[23, 24] on the kinetics of flow reactions. Then came a paper by MACMULLIN and WEBER[123] on the design of stirred tank reactors, and in 1943 the first rational formulation of the kinetics of solid catalysed vapour phase reactions was published by HOUGEN and WATSON.[94] Since the publication of these classical papers, the progress in the field of reactor design has been quite rapid. The first treatise on applied kinetics appeared in 1947 under the authorship of HOUGEN and WATSON.[95] This was followed by several books of varying scope and complexity.[105, 139, 167, 189]

Among the other significant landmarks in the development of this subject may be mentioned the following: address by K. M. WATSON in 1939 on the need for introducing applied kinetics in chemical engineering education; HOUGEN's comprehensive survey of applied kinetics in 1951[96]; two American symposia, one on reaction kinetics and mass transfer in 1952 and the other on reaction kinetics and unit operations in 1959; two European symposia on chemical reaction engineering in 1957 and 1960; and the introduction of the terms, "macro" and "micro" kinetics, by VAN KREVELEN.[185]

Mass Transfer Between Phases

One of the important considerations in reactor design is mass transfer between two phases. It is not the purpose of this article to survey this vast field, but it will be fruitful to indicate the various theories that have been proposed to explain this phenomenon.

The first theory put forward was that of equivalent films by HATTA[86] and WHITMAN.[194, 195] DANCKWERTS proposed an alternative theory, the so-called penetration (or surface renewal) theory,[38, 51] according to which there exists an unsteady-state situation with eddies of one fluid momentarily resting on the interface until displaced by other eddies coming from the bulk of the same fluid; during the time the eddies stay at the interface, unsteady-state mass transfer is supposed to take place. Recently, another theory has been proposed by SHERWOOD and RYAN,[164] according to which mass transfer takes place from a turbulent boundary layer between the phases. However, for all practical purposes, the several correlations worked out on the basis of the film theory can be used without sacrifice of accuracy.

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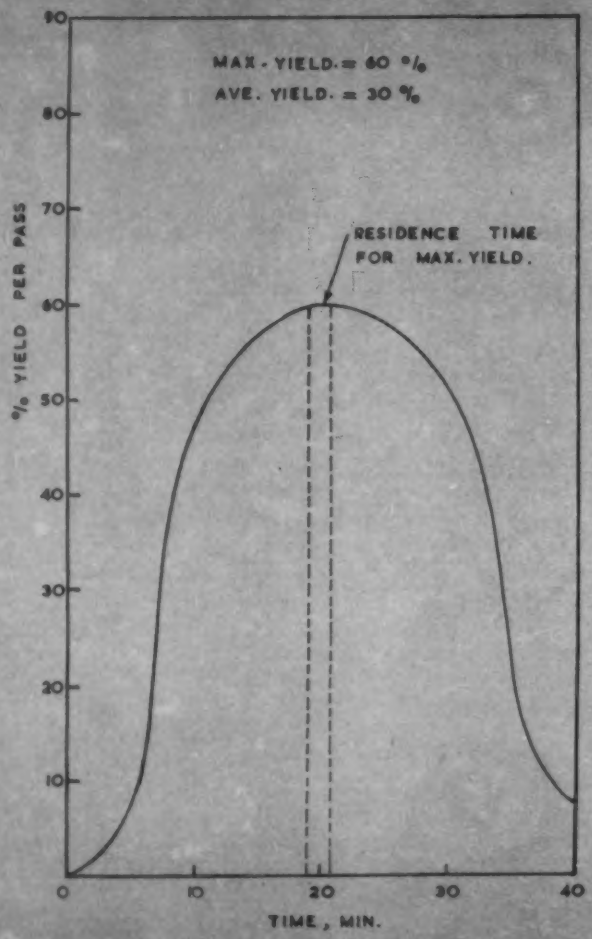
Fig. 1. Effect on conversion of residence time distribution.



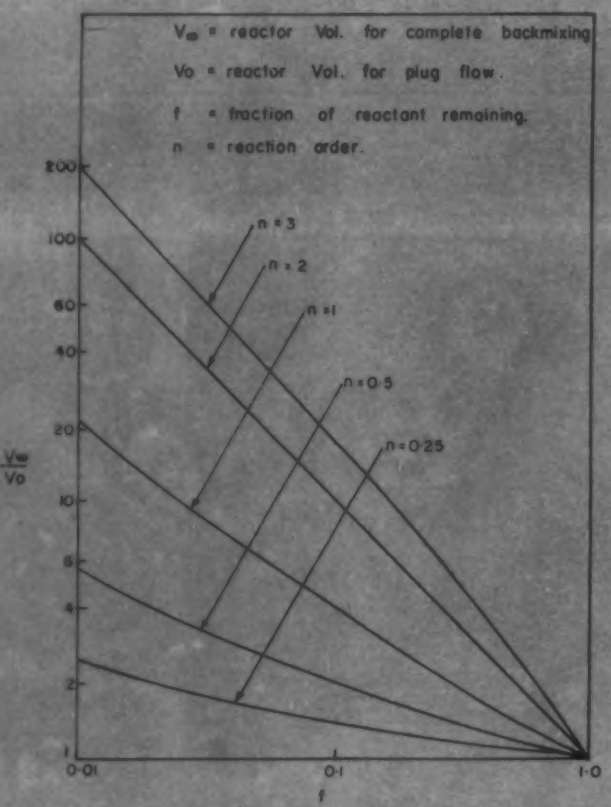


Fig. 2. Effect of reaction order and backmixing on conversion.

Classification of Reactors

In this paper, in order to critically evaluate the present status of reactor development, the subject is viewed not in terms of reaction systems but in terms of reactor types. The important types of reactors are the tubular reactors, stirred tank reactors, fluidized-bed reactors, adiabatic reactors and tower reactors. These reactor types are not mutually exclusive, as exemplified by the fact that a fluidized-bed reactor of the longitudinal type might easily fit into the definition of a tubular reactor, and any reactor can conceivably be an adiabatic reactor. Nevertheless, this classification is useful in presenting and analysing the more important basic equations and design procedures proposed so far.

Space Velocity, Hold-up Time and Residence Time Distribution

One of the principal parameters in industrial kinetics is space velocity which is a measure of hold-up time. The concept of space velocity leads directly to the definition of space-time-yield.[144] A mathematical analysis of space velocity and space-time-yield has been made by KODAMA *et al.*,[110] in which equations have been proposed for space-time-yield for isothermal, adiabatic and heat-exchange type reactors. Space-time-yield calculations have also been reported by WILHELM[196] for the oxidation of SO_2 in adiabatic and isothermal reactors.

Several investigators retain the concept of residence time in the formulation of rate equations in preference to the ratio of reactor volume to feed rate. This leads to unnecessary complications[96] like changes in density, compressibility and volume along the length of the reactor. When viewed against the background of the primary requirement of a useful rate equation, i.e., its ready amenability to the calculation of reactor volume, it becomes apparent that the introduction of residence time should be avoided—except when a distribution of residence times is involved.

In recent years the distribution of residence time in a flow reactor has been recognized as a significant factor affecting reactor performance. The use of average hold-up time in a flow reactor is based on the assumption that different streamlines of the fluid which enter the reactor at the same moment travel with equal (and constant) velocity and leave the reactor at the same moment. In an extreme case, however, it is possible that a fraction of the reactants may remain so long that side reactions or decomposition reactions may set in, leading to a sizeable fall in yield. This case has been discussed by SHERWOOD[162] for a first-order liquid phase reaction. He considers a batch reaction with a maximum conversion of 60 per cent at a residence time of 20 min; longer residence times lead to decomposition of the desired product. It is apparent from Fig. 1 that, in a continuous reactor, unless all portions of the reactants stay in the reaction tube for a period of about 20 min, the average conversion will fall to about 30 per cent.

Since the initial publications of SHERWOOD,[162] BOSWORTH[32, 33] and DANCKWERTS,[53] many original contributions[57, 112, 130, 156, 170, 179, 181, 192] have been made which have thrown light on several experimental and theoretical aspects of residence time distribution. For plug flow and fully mixed reactors, residence time distribution can be easily calculated, while, for reactors with intermediate flow patterns, experimental determination of residence time distribution becomes necessary. For first-order homogeneous reactions, this information is usually sufficient to predict reactor performance; on the other hand, for reactions other than first order more information is required.

Tubular Reactors

In tubular reactors one is usually restricted to the follow-

ing types of flow: laminar flow, turbulent flow and flow through packings. For laminar flow, the residence time distribution (calculated on the basis of hydrodynamics alone) may be combined with molecular diffusion to predict the output of the reactor. On the other hand, for turbulent flow and flow through catalytic reactors, it is necessary to distinguish between two rather extreme cases[111]: uniform velocity throughout the tube cross-section (piston flow) with superimposed axial diffusion; and non-uniform velocity profile where, as a result of an axial concentration gradient, adjacent streamlines will have different concentrations leading to radial exchange of matter either by molecular diffusion (streamline flow in catalytic reactors) or by eddy diffusion (turbulent flow). The first effect tends to increase the purely hydrodynamic spread in residence time, while the second tends to reduce it. In the rigorous design of a tubular reactor, all these factors should be fully evaluated. In practice, however, these have only been considered in varying degrees.

Homogeneous Reactors

In this article we shall only be concerned with the methods of reactor design on the assumption that the kinetics are known. However, it should be emphasized that, in the case of complex reactions, one of the significant factors to be evaluated prior to reactor design is selectivity. This has been studied in detail by CHERMIN and VAN KREVELEN.[45] In the absence of precise methods of determining the rates of individual reactions, a very useful graphical method has been suggested by HOUGEN.[96] It is desirable that more work should be done on the experimental determination of the rates of individual reactions in a complex reaction system.

The performance of homogeneous tubular reactors is characterized by the disappearance of a substance by chemical reaction and its transport in the longitudinal direction by diffusion (molecular or turbulent). Very large values of diffusivity would mean that the reactor resembles an ideally mixed reactor, while a zero value of diffusivity would point to the reactor operating as a plug flow tubular reactor with chemical reaction controlling. Equations have been proposed by several investigators[49, 53, 100, 192] for predicting conversions in these reactors on the basis of kinetic and hydrodynamic considerations. The influence of axial diffusion (backmixing) in tubular reactors and the design of "complete backmix" reactors has been quantitatively examined in recent years for reactions of different orders.[71, 117, 118, 119, 199] Backmixing results in an increase in reactor volume; this increase is greater for higher conversions and for higher order reactions, as illustrated in Fig. 2. The work of LEVENSPIEL and co-workers[118, 119] is a significant contribution to the evaluation of backmixing in chemical reactors.

The normal industrial practice is to employ high feed rates, thus ensuring plug flow. A practical method of designing a plug flow coil-type reactor for the thermal cracking of petroleum oils has been suggested by FAIR and RASE.[70] Their method is an extension of the procedure first developed by HOUGEN and WATSON.[95] Design procedures for homogeneous pyrolysis reactors have also been worked out by several other investigators.[133, 158, 168, 169]

The use of low feed rates (laminar flow) leads to a definite velocity profile and diminution of yield, but since operation at low feed rates would lead to shorter reactors, investigations on the performance of these reactors at low Reynolds numbers would be fruitful. A significant paper in this field is that of HOVARKA *et al.*[98] Since, obviously, lateral mixing is beneficial while longitudinal mixing is detrimental to the performance of tubular reactors, these investigators placed baffles at regular intervals in a tubular reactor and observed a break-up of the laminar velocity profile. Other significant theoretical papers on laminar flow reactors have come from DENBIGH,[61] BOSWORTH,[32] YOUNG[201] and CLELAND and WILHELM.[47]

An important factor in the design of homogeneous tubular reactors is the problem of mixing. DANCKWERTS[55, 56] has given a quantitative definition of the concept of mixing on a molecular scale. ZWIETERING[202] has defined a condition of "maximum mixedness" which represents one extreme state of mixing for an arbitrary residence time distribution. This definition should be helpful, since it is known that residence time distribution alone does not explain fully the mechanism of mixing in tubular reactors. Recently, GREENHALGH *et al.*[81] have compared three basic mixing models, e.g., plug flow, complete mixing and a combination of the two, for homogeneous reactions of several orders, and have proposed an application of their theory to reactor design when rate data and residence time distribution are known.

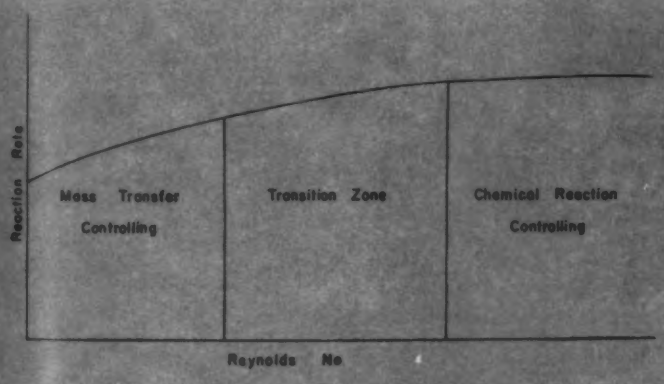


Fig. 3. Controlling steps in a solid catalysed gaseous reaction.

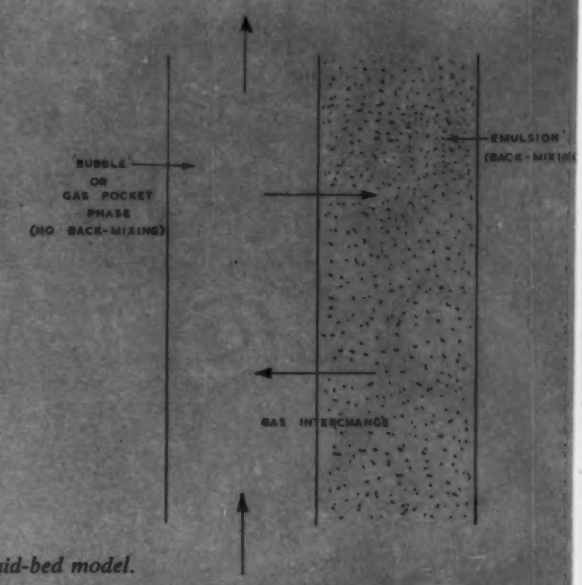


Fig. 4. Gas-solid fluid-bed model.

Heterogeneous Reactors

The design of tubular heterogeneous reactors involving vapour phase reactions on the surface of solid catalysts has received much attention. Rate equations for this class of reaction have been developed by HOUGEN and WATSON.[94] In spite of their many assumptions,[48] these equations still remain the best basis for the semi-empirical correlation of rate data. The general form of these equations may be written as [96]:

$$\text{Reaction rate} = \frac{(\text{kinetic term})\ (\text{potential term})}{(\text{adsorption term})^n}$$

These terms have been evaluated for different reaction types and controlling mechanisms by YANG and HOUGEN.[200] Recently, however, it has been pointed out by HOUGEN[97] that surface reaction should be rate controlling if the catalyst is efficient. It is therefore not necessary to consider the various other mechanisms, like adsorption of reactants and desorption of products. An interesting paper on the generalized correlation of the adsorption equilibrium constants is that of RASE and KIRK,[148] in which these constants are correlated with certain molecular properties in a homologous series. A practical method of determining reaction rates in a complex reaction has been demonstrated by BECKBERGER and WATSON.[21] It is surprising that more kinetic analyses of this kind have not appeared in the literature.

In the design of catalytic reactors it is necessary to consider temperature and concentration profiles, both in the radial and longitudinal directions. The basic nature of the problem involved has been indicated earlier. In addition to a reliable rate equation, the physical properties which must be known, but which are not readily available, for evaluating these profiles are effective thermal conductivity and effective diffusivity. Several investigations on the determination of these properties have been reported. The more significant contributions are those of ARGO and SMITH[14] and SAKAE YAGI and KUNII,[153] who have proposed methods for estimating effective thermal conductivities, and those of KIMURA *et al.*[108] and BERNARD and WILHELM[25] for effective diffusivity.

Several methods have been proposed for determining the non-isothermal character of catalytic reactors. In these methods, one of the two following models (explained earlier in this section) is usually assumed: uniform average velocity with temperature distribution transverse to the direction of flow, an average empirical heat transfer coefficient (or effective thermal conductivity) being introduced to describe the transfer of heat[93, 166, 188]; and uniform velocity distribution in which the variation of temperature (and concentration) transverse to the direction of flow is taken into account, thus allowing for radial variation of effective thermal conductivity and diffusivity.[19, 34, 102, 157] Other noteworthy methods for predicting temperature profiles are those of TING[175] and CHAMBRÉ.[41]

Based on either of the above models and using varying degrees of simplification, methods of catalytic reactor design have been developed by GROSSMAN,[83] TASKER,[172] WILSON,[197] SINGER and WILHELM,[168] BEEK and SINGER,[22] SMITH and collaborators,[84, 102, 157] BARON[19] and PASZTHORY *et al.*[141] Of these methods, the generalized graphical procedure of BARON is the most rigorous, and accounts also for radial concentration gradients in the bed. However, according to SMITH and collaborators,[157] a modified GROSSMAN method appears to represent the experimental data better than BARON'S rigorous procedure. RASE[147] has given examples of the use of kinetic data in the design of reactors,* and LEVENSPIEL and others[118, 119] have evaluated the effect of backmixing in tubular catalytic reactors.

In the design procedures listed above, it is necessary to have rate equations derived under such conditions that mass transfer is not operative. The uncertainty involved in using rate equations established without regard to the possible interference of mass transfer effects is evident from Fig. 3. Recently, HOELSCHER[90] has pointed out that rate data need not be obtained under this restriction. On the assumption that the thickness of the stagnant film surrounding a solid particle varies from zero to an upper limit according to a definite distribution function, HOELSCHER has developed an equation which takes into account both mass transfer and chemical reaction. It would be interesting to compare this method with the various other reported procedures.

Optimum Temperature (and Pressure) Gradients†

The assumption that isothermal reactors give the best performance is not always correct. In fact, it is possible to optimize yields by imposing a temperature gradient in the reactor, although this is difficult in practice. This problem has been considered by AMUNDSON,[4] who has presented a complete mathematical analysis of the temperature distribution between the fluid phase and solid surface, and by HORN and KÜCHLER.[92] The solutions of AMUNDSON are so complex that even machine computation becomes difficult. A simpler, generalized method for predicting the maximum or minimum temperature at any axial position has been indicated by HOELSCHER.[91]

For a reversible exothermic reaction, an increase in temperature leads to two opposite effects, viz., decrease in equilibrium conversion and increase in the rate of forward reaction. It is thus easy to visualize the existence of an optimum temperature at each cross-section of the reactor for the maximization of output. This problem has been discussed by DENBIGH[59, 63] and others.[6, 37, 173]

The theory of optimum temperature profiles in complex reactions has been worked out by BILOUS and AMUNDSON.[28, 29] Their mathematical analysis has led to a peculiar paradox: In the consecutive reaction,

$$A \longrightarrow B \longrightarrow C,$$

if the temperature coefficient of the first reaction is smaller than that of the second, a continuous decrease of temperature from the reactor inlet would result in an increased yield of the desired product (*B*). This would not be expected to be true if the temperature coefficient of the first reaction were greater than that of the second. The paradox lies in the fact that the calculations of BILOUS and AMUNDSON point to a diminishing temperature profile for this case also. Recently, ARIS[9] has used the method of dynamic programming for determining optimum temperature profiles for complex reactions in a tubular reactor. DENBIGH[63] has discussed the case of a complex organic reaction and has suggested that the use of a controlled temperature sequence would be as effective as selective catalysis to obtain the maximum yield of the desired product. This field has been explored sufficiently from the theoretical viewpoint, but there is need for experimental imposition of temperature gradients to verify these theories.

The effect of imposing a pressure gradient in tubular reactors has also been investigated.[182] This is of interest in reactions where the number of moles increases (e.g., dehydrogenation and dehydration reactions). Imposition of a decreasing pressure gradient in such reactions could result in a substantial reduction of reactor volume.

Stirred Tank Reactors

Stirred tank reactors are operated either batchwise or as continuous reactors (CSTR). An excellent analysis has been made by DENBIGH on the merits of batch and continuous operation.[62] All the treatments so far published on the design of stirred tank reactors approach the subject

* See also refs. [33] and [186] for the design of large reactors.

† The problem of reactor stability and control has also been discussed.[17, 38, 65, 126]

not in terms of residence time distribution, but on the assumption that the concentration of the outlet stream is the same as that within the reactor. In practice the stirred tank reactor does not conform to this assumption, and one is obliged to introduce an efficiency factor similar to that for the ideal stage in mass transfer operations.

One of the earliest contributions was that of KIRILLOV,[109] who proposed a general equation for the design of these reactors. MACMULLIN and WEBER[123, 124] have made a mathematical analysis of homogeneous reactions carried out in stirred vessels, and have also indicated a method for the computation of reactor volume for dissolution reactions. It is obvious that, in order to streamline the continuous stirred tank reactor and to minimize short-circuiting, it is necessary to divide the system into a number of well-stirred tanks. The efficiency in this case would be better than with a single stirred tank reactor. DENBIGH[60] has suggested that, for a given total volume of a battery of continuous reactors, the output of the system is greater when the reactors progressively increase in volume from the first; this situation is true for all reaction orders greater than unity.

ELRIDGE and PIRET[69] and JONES[104] have considered the case of higher order reactions, reversible, consecutive and simultaneous, and have proposed a graphical procedure for calculating reactor volume. They have shown that the flow from any reactor may be calculated independently of the order of the chemical reaction. TRAMBOUZE and PIRET[178] suggest that chemical reactions can be classified according to whether they are kinetically simple or complex (i.e., whether the reaction rate depends on one component or on several components), or whether the reaction is stoichiometrically simple or complex. They have also extended the graphical design of JONES for kinetically simple reactions to include kinetically complex reactions as well. LECLERC[115] has pointed out that the results obtained in a continuous stirred tank reactor are independent of the geometry of the reactor. If this were true, the scale-up of these reactors should be comparatively simple.

All the investigations referred to above are limited to steady-state operation. A condition of utmost physical importance is that of the transient approach to steady state. MASON and PIRET[126] have developed equations for simultaneous and consecutive reactions of the first order, and ACTON and LAPIDUS[2] have extended this treatment to second-order reactions. The question of purging before steady state is reached, and of starting and stopping a series of continuous stirred tank reactors, has also been considered[61, 122a]. KANDINER[106] has examined the case of a sudden change in feed composition and has presented charts for estimating the time lag. ARIS and AMUNDSON[7] have presented a statistical treatment to describe the behaviour of a CSTR under the small random fluctuations which occur even with the strictest of controls.

Heterogeneous reactions in stirred tank reactors have not received extended theoretical treatment. A method of calculating reactor volume in the case of a liquid-liquid system (organic sulphonations, nitrations, etc.) has been proposed by HOUGEN and WATSON.[95] Their postulation of "contactor efficiency" to account for agitational mass transfer in these reactors needs to be extended both theoretically and experimentally. Recently, REITEMA[150] has treated the liquid-liquid system as one in which the residence times of the two phases are of the same order and has proposed a design approach based on batch reactor data. FUGINAWA and MARUYAMA[73] and SEARLE and GORDON[159] give experimental data on liquid-liquid extraction accompanied by chemical reaction which should be a valuable basis for further work in this promising field. MATTERN *et al.*[128] have considered the theory of the design of CSTR for the industrially important heterogeneous system solid-liquid, and have suggested a design method for dissolution unaccompanied by chemical reaction. VAN DE VUSS[180] has proposed a method for the design of CSTR for gas-liquid reactions as exemplified by the oxidation of mercaptans.

Optimization in stirred tank reactors in terms of the different variables involved has been the subject of several investigations.[10, 11, 12, 64, 65] The observation by DENBIGH[64] that improvement in yield can be obtained by operating two stirred reactors at different temperatures has been extended by ARIS[11, 12] to several reactors in series. DENBIGH[65] has recently suggested a method of optimization by the so-called "maximization of rectangles" under a yield curve and ARIS[10] has applied the principle of dynamic programming for determining the optimum temperature for each of the reactors in a series of stirred tank reactors.

Tower Reactors

This class of reactors is generally used for gas-liquid, solid-liquid and gas-liquid-solid reactions. While in some cases the design of these reactors is similar to that of a catalytic tubular reactor, nevertheless, in view of the variety of reactions that can be carried out in these reactors, it seems justifiable to treat them separately.

In the case of reactions occurring on a solid surface, equations have been developed for flow past a laminar boundary layer where surface reaction of any complex kinetics may occur under isothermal conditions.[42, 43] Also, the effect on the rate of mass transfer of a very rapid homogeneous reaction between two chemical species has been examined both for a flat surface[72] and for a surface of arbitrary geometrics.[1] CHAMBRÉ[40] has considered the more general case of laminar and turbulent flows of non-isothermal character occurring in internal or external flow systems.

Another class of solid-liquid reactions that may be considered is ion exchange. The work done in this field is so vast that ion exchange is today treated as an independent unit operation.

Established concepts of mass and heat transfer have recently been applied to gas-liquid-solid reactions by HOUGEN and co-workers.[16] They have studied the hydrogenation of α-methylstyrene to liquid cumene on a catalyst surface, and have shown that kinetic equations of the conventional type for fluid-solid systems can be obtained using a so-called "trickling bed" reactor.

An important class of reactions is that between gas and liquid, i.e., absorption followed by chemical reaction. The standard text by SHERWOOD and PIGFORD[163] gives an excellent analysis of this class of reactions. These reactions are characterized by their kinetic order, degree of reversibility and the relative rates of the diffusional and chemical steps. Recently several studies have been reported[38, 58, 137, 151, 171] in which these reactions are explained either on the basis of the film theory or the penetration theory. TOOR and CHIANG[177] have made a mathematical analysis of diffusion-controlled chemical reactions as exemplified by the absorption of SO_2 in water. Gas-liquid reactions have also been studied by GILLILAND *et al.*[75] The design of gas-liquid reactors requires a knowledge of the liquid film transfer coefficient in the presence of chemical reaction. At present it is possible to predict these coefficients for first- and second-order reactions, reversible or irreversible[145, 163] and equilibrium reactions.[138] VAN KREVELEN and HOFTYZER[186, 187] have considered the application of the principles developed earlier for a graphical design of these reactors. By means of dimensional analysis, they have determined the number and character of the dimensionless groups that govern this process, and have proposed a graphical method for fast-reversible, fast-irreversible and moderate-fast reactions.

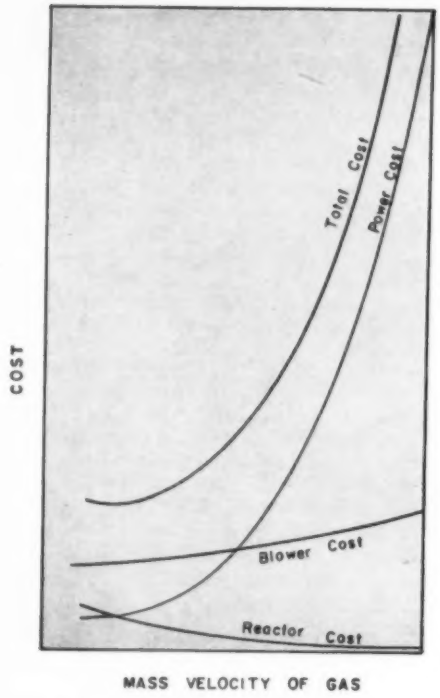


Fig. 5. Optimum cost of operation of adiabatic reactor.

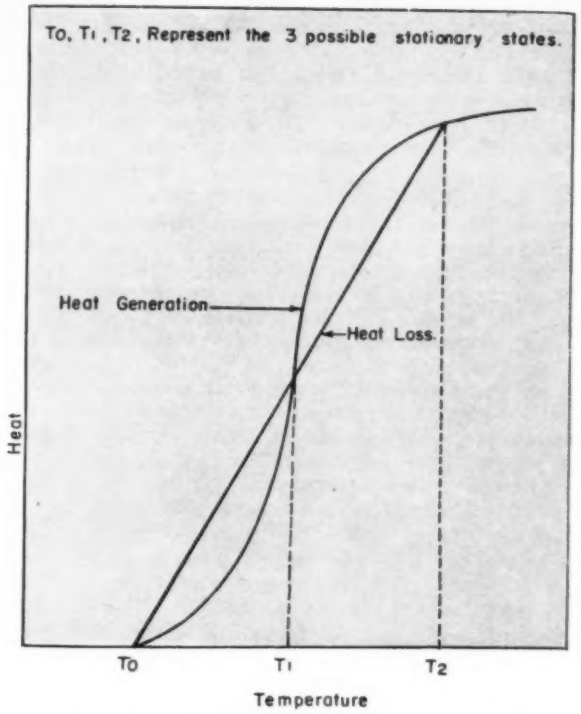


Fig. 6. Heat balance in an autothermal reactor.

Fluidized-bed Reactors

The fluidized-bed reactor is of the greatest importance in solid-catalysed vapour phase reactions (in particular exothermic reactions) and in the chemical treatment of ores (oxidation, chlorination, etc.). Fluidization does not affect the rate equation involved in the design of the reactor, but the flow characteristics of the fluidized bed come prominently into the picture and must be accounted for in any rational design of a fluid-bed reactor.

The earliest methods of designing a fluid-bed reactor, in which progressive or piston (or rod-like) flow was assumed and the rate equation integrated to obtain the height of the reactor, appear to have received confirmation in the work of GILLILAND *et al.*,[78] who suggest that the low conversion characteristic of a fluidized bed is due more to gas by-passing than to the absence of plug flow; DANCKWERTS *et al.*[54] have also shown, by measuring the residence time distribution in a large fluid-bed reactor, that the operation of this reactor is closer to piston flow than complete backmixing. The other extreme suggestion that the fluid-bed reactor may be regarded as a well-stirred tank reactor has not been borne out experimentally.[15, 76, 85, 149] More recently, the work of MAY[129] has shown that the efficiency of a fluid-bed reactor may vary from "better than fixed bed", in which case plug flow would take place, to "5 per cent of fixed bed", in which case a considerable amount of backmixing would exist. At the present time, a completely rational design of a fluid-bed reactor is not possible unless experimental residence time distribution data are available and the role of backmixing is fully evaluated. Even here the scale-up of the fluid-bed reactor would be difficult in view of the unpredictable relationship between the performance of a large reactor and that of a laboratory reactor. The primary difficulty involved in scale-up is the problem of gas by-passing referred to earlier.[78] A redeeming feature in the design of these reactors is that physical equilibrium between gas and solid is easily obtained and may be assumed.[46, 88, 99]

In fluid-bed reactors where the solids participate in the reaction, solids mixing becomes as important as gas mixing. The general solids flow pattern is up the centre of the column and down the sides,[76, 77, 132] with the downward-flowing solid particles creating some backmixing of the gas along the sides. Significant contributions in the evaluation of solids mixing are those of SINGER and others.[17, 79, 149, 165] Another difficulty involved in scale-up is that of bed uniformity; from the work of GOMEZPLATA and SCHUSTER,[80] it may be concluded that the fluidized bed is like an extraction column in which most of the conversion takes place within a short distance from the catalyst support plate and that the dynamics of bubble growth and travel in the bed should be known prior to reactor design.

In the evaluation of the performance of a fluidized-bed reactor, it is convenient to define an efficiency of the reactor. MAY[129] suggests the definition,

$$\text{Efficiency} = \frac{\text{Weight of catalyst required for piston flow}}{\text{Actual weight of catalyst}} \times 100$$

This quantity is always less than 100, since, in practice, it is found that more catalyst is required for a commercial unit than the quantity projected from pilot-plant data. Another definition is that of MATHIS and WATSON[127] who postulate an effectiveness factor for fluidization by analogy with the diffusional effectiveness factor of THIELE.[174] They have observed that this factor has a maximum value at an optimum fluid velocity.

Investigations on the performance of a fluid-bed reactor have also been made from an entirely different standpoint by several investigators.[121, 127, 129, 160] They have carried out a solid catalysed reaction of known rate in a fluidized bed, determined the overall conversion under different conditions, and have synthesized models that would account for the observed results. From an examination of the various models proposed, the general ideas incorporated in them may be

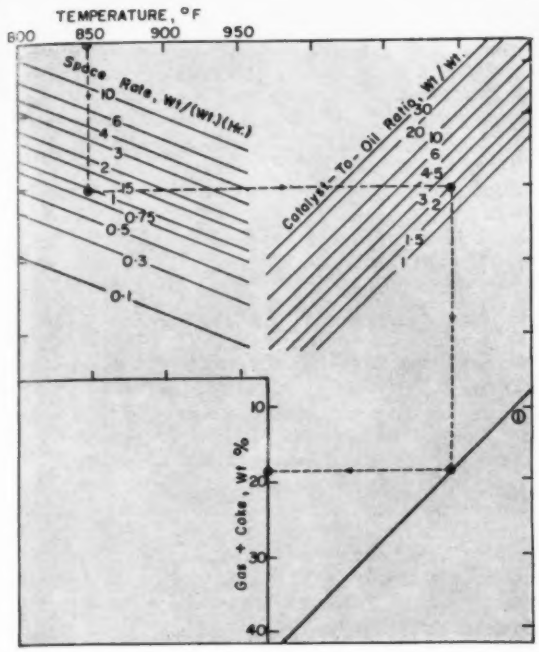


Fig. 7. Effect of operating variables on yield of gas plus coke in a Thermofore catalytic cracking process.

summarized as follows: the bulk of the gas rises through the reactor as bubbles without backmixing; the rest of the gas forms the so-called gas-solid "emulsion"; exchange of gas occurs between the "gas pocket" or "bubble" phase of the reactor and the "emulsion" at a rate which is independent of bed height; chemical reaction occurs in the emulsion phase only and the gas bubble has no catalyst in it; and the bed may be vertically unmixed with only horizontal mixing, or completely mixed. A schematic representation of this behaviour is shown in Fig. 4, which is self-explanatory. Reaction rate data may be usually correlated on the basis of a model of this kind with the help of the kinetics of the reaction which may be determined in a fixed-bed reactor. It is necessary that more work of the kind reported by MATHIS and WATSON,[127] in which fixed and fluidized-bed reactors have been experimentally compared, should be carried out.

Several designs of fluid-bed reactors are available in the patent literature. An important design factor pointed out by CORRIGAN *et al.*[48] is the unstable operation of a multi-tubular fluid-bed reactor. They have suggested the introduction of orifices of appropriate sizes to prevent the solids from one tube being completely blown into another. With the available information on the characteristics of fluidized-bed reactors, it does not seem possible to design a commercial fluid-bed reactor without going through one or more pilot-plant stages.

Adiabatic Reactors

In an adiabatic reactor the reactants enter at a predetermined temperature and the products of reaction leave the reactor at a temperature determined by the reactor dimensions and the thermal characteristics of the reaction. Heat is neither supplied to nor removed from the reactor. A rigorous design procedure for this kind of reactor is presented by HOUGEN and WATSON[95] both for homogeneous and catalytic reactors. The performance of a reactor for the hydrogenation of codimer has been compared for isothermal and adiabatic conditions of operation[96] and it has been shown that, when operating adiabatically, the volume of catalyst rises to infinity beyond a certain temperature, while, under isothermal conditions, it decreases with temperature. RAO and HOUGEN[146] have examined the adiabatic operation of a reactor for the oxidation of nitric oxide and have found that it is simpler to use an adiabatic reactor since no particular advantage is gained by isothermal operation.

One would normally expect the adiabatic reactor to be used for exothermic reactions only, but recently a graphical method for the design of an adiabatic reactor for endothermic reactions has been proposed.[161] It is also claimed[3] that the proposed method can be used for the approximate calculation of reactor volume from experimentally determined isotherms thus obviating the need for a rate equation.

In determining the optimum cost of operation of an adiabatic reactor, it would be necessary to consider reactor cost, pumping (or blowing) cost, and power cost as functions of mass velocity and arrive at the optimum velocity of the reactants as shown in Fig. 5. If the mass velocity is reduced excessively in order to minimize pressure drop, the required diameter of the bed becomes so large that distribution difficulties would result, leading to channelling and backmixing. On the other hand, an increase in mass velocity reduces the diameter of the bed required, but this advantage is rapidly upset by the increased pressure drop in the bed, leading to increased power requirement for pumping or blowing. These aspects of adiabatic reactor design have been critically examined by RAO and HOUGEN. The optimum design of an adiabatic reactor has also been examined by ARIS,[8] who suggests a mathematical procedure for choosing the size of each bed in an adiabatic reactor and the degree of interstage cooling between beds.

VAN HEERDEN[183] introduced the term "autothermal reactor" for a reactor which is thermally self-sustaining. This reactor can be used for exothermal reactions only, and its performance can be gauged by means of a simple diagram which shows heat loss and heat production as functions of temperature (Fig. 6). A completely mixed, continuous adiabatic reactor is considered, and it is shown that this system involves the possibility of three stationary states at which heat production and heat loss balance with each other. A complete analysis of the design of these autothermal reactors has been made by VAN HEERDEN in a subsequent paper[184] in which he has considered the following cases: continuous mixed reactor, reactor with piston flow and heat exchange between outlet and inlet, and reactor with piston flow and axial conductivity of heat. He has discussed the conditions under which more than one stationary state may exist for these reactor systems. In another publication,[143] a design procedure is proposed for these reactors. Information is also available on the operation of autothermal reactors.[131]

Miscellaneous Design Procedures

In the foregoing paragraphs, the rational design of different kinds of reactors has been reviewed. Quite often, however, in view of the lack of basic information on such factors as degree of mixing, effective diffusivity and effective thermal conductivity, and the absence of a reliable rate equation, these generalized procedures may not be applicable. The demands of the chemical industry are urgent, and a process engineer is therefore often called upon to find short-cut procedures, empirical or semi-empirical, to arrive at reasonably sound designs. The following are some of the useful procedures proposed.

Graphical Procedure

Where exact rate equations are not available, rate data

may be correlated in terms of a pseudo-first-order reaction rate; instances of this may be found in the petroleum industry. HOUGEN and WATSON[95] have suggested a method for obtaining first-order correlations. For the low conversion range the reaction rate factor is plotted against the reciprocal of space velocity, while for the higher conversion range the reciprocal of the rate factor is plotted against space velocity. The applicability of this method has been demonstrated by DORAISWAMY *et al.*[67] in the case of the thermal cracking of ethylene dichloride to vinyl chloride. The principal advantage of this method is that complete design equations, both for the low and high conversion ranges, can be obtained with the minimum number of experimental points (a single point is often sufficient).

Nomographic Presentation of Data

When it is not possible to arrive at any rate equation due to the extreme complexity of the reactions involved, the best procedure is to represent the rate data graphically in such a manner that most of the information can be obtained from a single plot. A procedure of this kind has been followed by the Houdry Corporation[155] for a Thermofore catalytic cracking unit. In this process, rate data were obtained for the cracking of an American heavy oil, the operating variables being reactor temperature, space velocity and catalyst-to-oil ratio. The graphical method is shown in Fig. 7, in which the dotted reference line is applicable to a specific oil stock; reference lines for other stocks can also be drawn. The principal advantage of this method is that it involves no ambiguous rate equations and the effect of changes in operating variables on product distribution and yield are readily shown.

"Equivalent Temperature" Method

One of the main difficulties in the design (and comparison) of chemical reactors is that temperature variations must be accounted for. This may be overcome, to some extent, by the use of the so-called "equivalent reaction temperature", which is defined as the temperature that would give the same conversion as an actual reactor operating under non-isothermal conditions. This concept, which was originally proposed by HOUGEN and WATSON,[95] was later extended by OTAKE *et al.*,[140] MALLOY and SEELIG[125] and TING.[176] Equations have been proposed by the latter workers to enable the calculation of approximate reactor volume from isothermal rate equations. An experimental method for determining isothermal rate data from non-isothermal tubular reactors has been suggested by LEE *et al.*[116]

The concept of equivalent temperature has been extended to include variations in pressure in the reactor.[95] The combined effect of variations in pressure and temperature may be expressed by means of the so-called "severity factor" in terms of reaction at atmospheric pressure and an equivalent temperature. Extension of this concept to industrial design should yield very favourable results, but no publications have so far appeared in this field.

The *HRU* Method

Based on the observations of LAUPICHLER,[114] HURT[161] proposed the concept of the height of a reactor unit for the design of chemical reactors in which mass transfer is also taken into account. For first-order reactions HURT proposed the expression,

$$HRU = HCU + HTU,$$

in which the term *HTU* accounts for mass transfer of reactants to the catalytic surface, *HCU* represents the height of the catalytic unit for the reaction, and *HRU* the total height for mass transfer and chemical reaction. This principle of additive resistances was extended by HAY *et al.*,[87] who showed that it is applicable regardless of the number of resistances involved, e.g., adsorption, chemical reaction, desorption, mass transfer, etc. CADELL and HURT[36] showed that the *HRU* concept can be used for reactions of all orders by treating them as pseudo-first-order reactions. Recently NARSIMHAN and DORAISWAMY[134] have extended the definition of HURT to include mass transfer of the products from the catalyst surface to the bulk, and have suggested a procedure by which this method can be extended to include reactions other than first order. Applications of the *HRU* concept to reactor design have been published by PERONA and THODOS,[143] BLACK *et al.*[31] and NARSIMHAN and DORAISWAMY.[134]

Factorial Design and Use of Computers

In the case of a complex reaction, in which rate-controlling steps are difficult to determine, a statistical approach designated as factorial design is fruitful. The factorial effect is a measure of the response of the system to a shift from low to high levels of an operating variable without calling for changing just one variable at a time. The number of variable experiments in a factorial approach is given by 2^n, where n is the number of significant variables controlling the reaction rate. Several papers have been published on the application of this method to reactor design, the more important of them being those of BARNET *et al.*,[18] CARR and MECRACKENS,[39] CHANG *et al.*[44] and GROHSKOPF.[82]

The use of computers in the design of chemical reactors is receiving increasing attention. The computer programme has become so vast that it is outside the scope of this review. Among the useful papers that may be referred are those of BILLINGSLEY *et al.*,[26] GEE *et al.*,[74] NILSON[136] and SNOW *et al.*[168]

Use of Batch Data for Continuous Reactors

In conclusion, a brief reference will be made to the design of continuous reactors from batch data. In the case of homogeneous reactions, the transition from a batch process to a process carried out in an ideal continuous tubular reactor, or to one carried out in an ideally mixed continuous tank reactor, is relatively simple. However, where there are deviations from ideality, as would be the case in practice, it is impossible[53, 59, 156] to predict the performance of a continuous reactor on the basis of batch kinetics if the order of the reaction involved deviates from unity.

For heterogeneous reactors, the difficulties involved in translating batch to continuous kinetics are much more serious. REITEMA[150] has suggested a method for liquid-liquid reactions, and DORAISWAMY *et al.*[66] have proposed a practical procedure for solid-fluid reactions in which the solid participates in the reaction.

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CONTRIBUTIONS TO THE CRUSHING AND GRINDING LITERATURE IN 1960

by J. NIJMAN

An outline is given of trends in technical and scientific progress in the 1960 literature. It is found that critical surveys of existing theories, together with a number of valuable original contributions, elucidate many aspects in this field.

This is particularly the case in grinding, although the same trend is found in coarse crushing, where a number of papers point out how better understanding can be reached, notwithstanding the many difficulties encountered there

MANY valuable contributions to the literature on crushing and grinding have been made during the year, giving data on plant experience on the one hand and enlarging the scope of theoretical knowledge on the other. Moreover, existing theories have been criticized. This seems to indicate that crushing and grinding are well on their way to exchanging experimental status for a scientific one. Nevertheless, it can also be concluded that much work to that effect is yet to be done.

Need for more knowledge on particle disintegration is also felt in other branches of the science of powders, as was repeatedly mentioned for instance during the London conference on Powders in Industry.[1]

The reverse is, of course, also true. Progress in particle separation,[2, 3] particle size measurement,[4] adhesion of particles,[5] dust prevention and measurement[6] is of vital importance for experimental purposes, so that these random examples might illustrate that need is felt for closer collaboration between the different subjects into which knowledge of the solid state is historically divided. Maybe this trend is also present on the engineering side, as might be concluded from many of the papers mentioned in the following and from the appearance in 1960 of a new German periodical, *Aufbereitungs Technik* (processing preparation), which in the first year of its existence covered many sides of its subject with interesting papers.

In the following a number of papers have been mentioned and reviewed to some extent. The object has been to give an outline of trends in technical and scientific progress, illustrated by a number of references that is only complete in so far as it should prove the points mentioned by the author.

Theory of Disintegration

Von Rittinger and Kick's laws still are the starting point for many theoretical discussions, but as a result of better understanding of particle behaviour during comminution, the controversy between the two is no longer there. Many authors discuss the relation between size reduction and energy input with great care, as it is now generally accepted that this relation will depend on many factors. Hence only a very few papers have this relation as their main topic,[7] indicating that energy consumption of comminution devices is no longer the starting point for theoretical considerations, but is recognized as the final conclusion from them.

A critical survey of existing theories is given by KELLEHER,[8] who concludes that Bond's law is still important for design purposes, although it has some of the shortcomings of the Rittinger and Kick theories. Therefore, Holmes' law is preferred, as it incorporates differences in particle strength as well as the kind of force used in a size reduction machine. It is interesting to note, however, that it is assumed that particles have the same form all along the size range. REY[9] states that the shape of a particle formed depends on the mill used, while MÖLLING[10] thinks Jakobis theory is more elucidating in the case of coarse crushing than Andreasen's concept of breakage.

Also on the subject of disintegration phenomena, KERKHOF[24] discusses the physical principles of breakage events.

Many papers appeared on fundamental theory of specific comminution devices. Often they are of direct industrial importance because of their far-reaching conclusions.

The theory of jet disintegration is thoroughly treated by RUMPF[11, 12] and REINERS.[13] RUMPF discusses Knethe's theory on the movement of particles in a gas jet from experimental evidence, while in his second article he deals with the communition mechanism in jet mills. It is stated that comminution laws are of value for statistical and dimensional analysis only, as a result of the influence of particle shape on stress distribution in the particle before breakage. Still RUMPF is able to draw conclusions about the application and the limitations of jet mills. REINERS' paper contains interesting information from high-speed camera pictures on the breakage phenomenon itself, showing evidence again that the shape of the particle formed is a function of many factors. From these three papers valuable insight in jet milling is obtained.

An interesting experimental and theoretical article by BATEL[14] on pin-disc mills shows that the size reduction reached in these mills is mainly the result of one impact only, while air movement in the mill appeared to have no effect. Conclusions regarding construction of these mills are also given.

Tumbling mills are discussed in several papers. LIU[15] deals in great detail with the movement of the charge in a

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ball mill and derives a technique to calculate optimum ball load as a function of rotational velocity, that is, the interdependence of the two is recognized and covered mathematically. While he seems to be unaware of existing theories, his work is in a way complementary to these. The work of HALBART and FREYMANN,[31] partly on the same subject, is referred to later in this review. GUERRERO and ARBITER[21] also discuss the movement of the charge in a tumbling mill. While stressing the fact that dimensional analysis can only give an empirical procedure to correlate data, Davies' theory is critically reviewed and found to give optimistic results for effective energy use. This is because Davies disregards liner movement relative to the movement of the cataracting balls, which means that the balls lose energy in changing from the parabolic to the circular path. When incorporating this, closer agreement with experimental results is obtained. While this certainly means the perfecting of existing theory, BOND[34] in a paper on rod mills proposes the application of the theory of harmonic oscillation to rod movement. As he admits that the "average" rod motion is undoubtedly more complicated, his concept appears to be oversimplified. The optimum loading in ball mills is also discussed by MASSON[16] for dry grinding in laboratory experiments, while KOULEN[17] gives a literature survey with many references on closed circuit grinding.

HUKKI[18] covered ball mill characteristics below and above critical mill speed. It is again felt that careful consideration of his work on supercritical mill velocities should lead to extensive industrial application in future.

Ball mills were studied for their mixing ability by DINTELFASS,[19] using pigment dispersions in extensive research covering many factors influencing dispersion.

Vibratory mills now seem to claim universal interest. Frictional as well as impact milling was found to play a role by GEL'PERIN and POLOTSKII[20] in a laboratory investigation of the influence of feed volume, ball volume and ball diameter at various milling times on four minerals. An empirical connection between different variables was found to exist. Both types of disintegration mentioned have been studied separately.

FÜRSTENAU[22] discusses the retention time in continuous vibratory mills. For open circuit dry grinding of chromium ore he extends Holmes' theory to continuous vibratory milling.

MATVEEV[23] describes a laboratory research on wear of ceramic grinding bodies in a 10-litre vibratory mill, while ROSE[25] discusses the principles of these mills. It should be mentioned at this point that Rose and Sullivan's book on "Vibration Mills and Vibration Milling"[26]—that according to the editors should have been out in 1960—was not yet available, but is said to contain a valuable contribution to the literature on the subject, largely based on experiments from their own laboratory.

A number of papers on crushers appeared that contain information allowing better understanding of industrial design. Although the authors state that exact calculation is impossible in this field, more insight in the problems encountered has been obtained, and some interesting conclusions could be drawn.

A mathematical calculation technique for jaw and gyratory crushers was proposed by SOMMER.[27] The method described is based on empirical facts, but the formulæ derived are said to have been proved in practice and can be used for design and checking calculations. CALCOTT[28] gave a preliminary report on the study of the mechanism in a 15 × 8 swing hammer mill. He concluded that the action of the mill is primarily by impact of the hammers and the breaker plate or breaker bars. His high-speed camera study is not yet complete, but it is hoped to tell more about the breaking process. Many experimental difficulties are encountered that obscure the influence of grindability on selective breakage, but first conclusions seem to indicate that selective breakage is absent in the primary impact zone.

There is a remarkable agreement between CALCOTT'S findings in the swing hammer mill and BATEL'S earlier-mentioned conclusions from his pin-disc mill study, although CALCOTT remarks that near the gap between hammer tips and breaker bars the size reduction is effectively a form of localized close-circuit grinding. The use of matrix analysis looks complicated at first sight, but should certainly not discourage those interested in this promising approach.

Fundamental problems in coarse crushing are discussed by MÖLLING.[10] From a critical survey of existing knowledge it is concluded that one of the major difficulties encountered is the variation of strength of large lumps. This is illustrated by cited Russian experiments. The use of a size reduction factor is advised against, and energy input calculations according to BOND or SVENSSON and MURKES are said to be often erroneous.

FRENKING[29] in a three-part paper reports on investigations of the interaction of forces in a beating crusher. Development of crushing techniques and electronic measuring and control devices is said to be indispensable for future investigations. From 65,000 readings, frequency analysis led to a number of conclusions, of which perhaps the most important one is that a relation has been established between force, kind of rock and crusher adjustment. The variation of torque as a function of time was studied in order to have a simple means to determine the energy input per stroke. It is thought that conclusions drawn can be regarded as a close approximation to the real situation. The plotting of the results permits determination of total energy and elastic energy spent on the rock separately. From this it may be concluded that FRENKING'S approach to this difficult subject is sound and will eventually lead to still better understanding of coarse crushing.

Industrial Applications

There is no strict division between theory and industrial application, as in many instances the two are closely interwoven, meaning that theory is working its way into industrial practice more and more.

This is particularly the case in the field of liner wear.[30, 31, 32, 33] MATOUSHEK[30] published a mathematical approach by way of statistical analysis, with many references on the subject. The ideal solution is said to be in combined effects of proper choice of alloy and surface and shape of the liners. On the other hand, HALBART and FREYMANN,[31] discussing Davies and Ugglia's theory on the movement of the charge within a mill, conclude that the space in between liner bars is essentially connected with ball diameter. Ball packing geometry is considered, a thing that is overlooked by many authors. A liner construction is proposed in which the distance between bars is smaller towards the discharge of the mill. This causes worn (smaller) balls to move towards the finer milling zone. Proper attention is also given to the coefficient of friction between different rows of balls.

BOND'S article on rod mills[34] deals with an industrial example. As it was found that the energy consumption and throughput did not agree with the Bond index, close observation of the rods was made. It was found that rods wear to a certain thickness and then break. 4 tons out of 63 tons of rods were thus found to have been broken. When broken rods are taken into account, the index appeared to be correct.

Cement mills are discussed by JACOB,[35] BEKE[36] and GINSBERG.[37] While JACOB discusses maximum mill output with the aim to determine the possibility of producing a finer product with an existing mill, BEKE concludes that for different types of cement different mills should be used.

GINSBERG confirms BEKE'S views from experiments in vibratory mills. His conclusions are that vibratory mills are

not suitable for clinker grinding in the cement industry, but show energy consumption advantages over ball mills for fine grinding. He recommends the replacement of conventional three chamber mills by two separately working units, and to use vibratory mills in the second grinding step.

Choice of primary crushers is discussed by MÖLLING[40] and experiences with hydrocone-crushers by MOTEK.[41] Use of semi-automatic pan mixers is described by KUHLMANN and DIETRICH.[42] Crusher control has been taken up by CAHALAN and WOLSKI.[43]

A paper by KÖTSCHAU and FRANKE on the use of devices regulating the fineness of screening in milling plants also covers control systems for mills in closed-circuit grinding.[44]

New machinery has not been mentioned in the foregoing. The interested reader is perhaps best referred to a detailed description of what has been shown at the 1960 exhibitions in Hanover, Munich, Mailand, Basle and Paris.[45]

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FLUIDIZATION

Much current work attempts to elucidate the dynamics of fluidized systems. Particular attention has been given to the role of bubbles in gas fluidized systems, but no adequate model of behaviour has yet been proposed. Further work on pneumatic conveying and elutriation from beds has been reported. Little recent work has been published on mass transfer. It has become more apparent that the localization of temperature gradients within turbulent beds is largely responsible for their thermal properties. Recent industrial applications are briefly reviewed. Consideration is given of spouting bed studies

by J. S. M. BOTTERILL

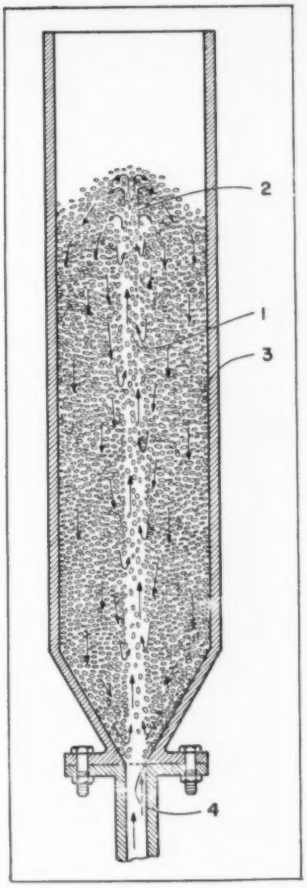

Fig. 1. *Spouted wheat bed.*

TWO recently published books[26, 55] well illustrate the present understanding of fluidized systems. LEVA[26] particularly gives a full review of working correlations. He shows that there are marked discrepancies between those proposed by different workers. In recent articles[27, 28] LEVA has summarized the correlations which, in his wide experience, are more generally valid. The treatment in the book by ZENZ and OTHMER[55] leaves an impression of the stark inadequacy of the existing fundamental approach. Correlations are often contradictory because relevant variables are not appreciated, factors due to the apparatus are unwittingly included and great difficulties are encountered in any attempt to measure the relevant properties of fluidized systems. The dynamic complexities of gas fluidized systems, in particular, defy adequate fundamental prediction. So it is that recently much research effort has been devoted to trying to gain better understanding of the dynamics of gas fluidized systems. Comparatively little work has been reported on heat and mass transfer apart from fundamental studies. Interest is developing in fluidized solids conveying and, for adequate understanding of this and because of the fundamental interest, in elutriation. Some general papers on industrial experience have been published and so have several papers on spouting bed techniques.

Bed Dynamics

The formation of pockets or bubbles in gas fluidized systems, when the fluidizing velocity exceeds that for minimum fluidization, is of considerable importance. The rising bubbles cause vigorous movement of the solids dense phase which is largely responsible for the good heat transfer and solids mixing properties of the bed. It is also through bubbles that reactant gases may by-pass the bed, giving disappointingly low conversion efficiencies.

DAVIDSON *et al.*[10] have measured the velocity of rise of bubbles resulting from the release of gas pulses at depths up to 35 cm in gently fluidized beds. Behaviour was similar to that of gas bubbles in an inviscid liquid. The rate of rise, U, was apparently independent of the main air flow rate and of the size and density of the particle under their experimental conditions being related to the corresponding liquid bubble volume, V, by the simple semi-empirical formula:

$$U = 0.792\, V^{\frac{1}{6}}\, g^{\frac{1}{2}}$$

Many studies have been made of general bed behaviour. DOTSON,[11] using a capacitance probe technique in beds 10 ft deep and of 4 and 24 in. diameter, found that all operating variables other than height had measurable influence on uniformity of density through the bed; the distributor had only local effect and gas velocity was the most important variable. BAUMGARTEN and PIGFORD,[7] using a radiation absorption technique, noted that the size of bubbles detected increased with height up the column. They pictured the dense phase becoming unstable; that there was a frictional resistance to gas flowing from the dense to the nascent bubble so that there was a finite time for bubble formation. Since the velocity of rise of bubbles increases with volume, larger bubbles overtake and coalesce with the smaller ones. They also suggested that the gas velocity in the dense phase

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drops to a value close to that of minimum fluidization. In general, cracking catalyst behaved more stably than the cuts of glass spheres. Their observations are largely in accord with those of other workers.[11, 24, 34, 54]

Some workers suggest that the bubbles rise by pushing aside the particles above, and thereby remain practically free of solids, whereas others suggest that there is a constant rain of particles through the bubbles. MASSIMILLA and WESTWATER[34] analysed high-speed photographs of bubble behaviour at the wall of their 3.75-in.-diameter column. According to bed conditions, they noted both forms of bubbles and a surprisingly marked tendency for aggregates of particles to persist. At lower gas flow rates they observed small bubbles, free of solids, rising rapidly through the bed, overtaking and coalescing with smaller bubbles and thereby growing. At higher gas flow rates unstable pockets predominated, through which there was a constant rain of solids. It is, however, questionable whether or not, at this extreme, there was a tendency towards slugging rather than bubbling because of the dimension of their apparatus (though YASUI and JOHANSON,[54] in their work using a light probe technique, concluded that such a rain of solids occurred). The rain of solids, if it generally occurred, would give better contact between reactant and catalyst and consequent improvement in reactor efficiency, compared with small solids free bubbles rising through the bed.

LANNEAU,[24] using a capacitive probe technique in a very deep and narrow bed (30 ft deep, 3 in. diameter), noted discrete well-formed bubbles low in solids at his lower fluidizing gas velocities (0.1-1 ft/sec; minimum fluidizing velocity 0.02 ft/sec). His probe measurements showed that the expanded bed density increased when bubbles began to form. This was presumably due to gas seeping into the bubbles from the dense phase. At higher gas velocities he considered the picture of solids raining through the bubble to be the most realistic. Developing theoretically the consequences of bed behaviour in which gas transfer was only associated with the transfer of solids and which assumed the bubble velocity to be numerically equal to the superficial gas velocity in a régime where slugging would prevail, his model predicted marked gas downflow through the emulsion phase. That this should occur is hard to believe, and suggests that the model is unreliable in such extreme conditions.

MAY[35] studied similar problems of bed behaviour in reactors up to 5 ft in diameter and 35 ft in depth, but for bubbling rather than slugging conditions. From tracer studies he followed the solids mixing and found that it was by a diffusional mechanism in a 15-in.-diameter column, but that gross circulation patterns distorted this in the larger diameter column. MAY estimated cross flow from experiments using a helium tracer. Although possessing advantages over more inferential methods, it is not an easy technique to use in these circumstances. He noted that back mixing has negligible effect with low cross-flow ratios. Despite high mixing rates in large-diameter beds, such beds can be very far from being completely mixed as far as the reaction is concerned. His simple model of cross flow from the mixed emulsion phase to the bubble phase did not consider the effect of the presence of catalyst inside the bubbles. This would have a particularly marked effect when the cross-flow ratio is low and the conversion level high. MAY extended his theoretical development to a consideration of the effect of poor contacting on the selectivity of two parallel first-order reactions. He showed that poor contacting will reduce differences due to chemical activity. In such poor conditions, all the reactants that got into the emulsion would be converted.

Neither of these two papers[24, 35] offers an adequate dynamic model of the process by which bubbles survive in fluidized beds and which must, in the case of regular capped bubbles, involve leakage of gas from the cap of the bubble. But both authors in their theoretical treatment develop the implications of cross flow, however it may occur, and their conclusions may act as salutary warnings. That although, under certain conditions conversions in fluidized beds may be higher than those obtained in a corresponding packed bed, under other conditions they may be less than one-twentieth.

GOMEZPLATA and SHUSTER[19] have studied the overall conversion from the catalytic cracking of cumene in beds of 1.5-8 in. depth and 3 in. diameter. Their results indicated that the first few inches of bed were very much the most effective in bringing the continuous and discontinuous phases into contact over the superficial gas range used (0.06-0.24 ft/sec). This can be explained in terms of the rapid growth of gas bubbles as they rise through the bed, reducing the effective contact. With much higher gas velocities, if a rain of solids through the bubbles occurred, the results might be quite different. The experimenters observed that markedly better results were obtained when using a porous plate support instead of a screen. This is attributable to better initial gas distribution.

LEWIS *et al.*[25] attempted to find an adequate model of their reactor behaviour by using a reaction with known kinetics (solid catalysed hydrogenation of ethylene). They assumed that at any given level the gas composition was uniform within the given phase, but not necessarily the same in the two phases; that the rate of reaction was dependent only on gas composition and the quantity of catalyst in contact with it in that phase. Whilst considering interchange of gas between the bubble and emulsion phases, unlike LANNEAU,[24] they assumed that there was no general back current of gas through the emulsion phase. One model, which fitted the experimental results well, assumed that the emulsion phase was only mixed in the horizontal direction. The more complicated model of a completely mixed emulsion was less amenable to the test of calculation. However, they concluded that under the chosen experimental conditions approximately the same result was to be expected, so no conclusion could be reached with regard to models of back mixing in the emulsion.

Using a capacitive probe technique,[2] BAKKER and HEERTJES have assessed the long-term porosity distribution over a gas fluidized bed.[3] They observed that there was a regular porosity distribution in their experimental bed (9 cm diameter) which persisted over a wide range of fluidizing velocities. In general, the bed could be divided into three regions: the entry section of decreasing porosity from the bottom of the bed; the middle zone of nearly constant porosity; and the top zone, where particles are sprayed from the bed surface as bubbles break. It was suggested that wall effects would be diminished in a larger bed, but that there should still be the stable porosity pattern, particularly in the middle zone. From consideration of a gas balance in the middle zone, a simple equation relating porosity to fluidizing velocity was developed.

The use of baffled systems as a means of overcoming the disadvantageous effects of gas by-passing have been reported.[25, 34, 36] These systems have the additional advantage that co- or counter-flow can be achieved without seriously reducing gas or solids throughput or solids hold-up. MASSIMILLA and WESTWATER[34] noted that a well-baffled bed may, however, be more like a fixed bed than a free fluidized bed from the point of view of solids circulation. OVERCASHIER *et al.*[36] made a fuller study of the effect of baffles on gas residence time. Although the residence time spectrum was narrowed by the use of baffles, it was not reduced to that of a perfectly mixed unit. Whereas gas velocity had no significant effect in unbaffled beds, it had a marked effect in the baffled system. This is in accord with the results reported by LEWIS *et al.*[25] Of the five models considered by OVERCASHIER *et al.*[36] for the behaviour of the baffled system, no unambiguous selection could be made.

Particle diffusivities and speeds at the wall of a column (particle velocities increased with fluidizing gas velocity) have been assessed by visual techniques.[34] GAVIN *et al.*[17] have used radioactive tracers for measurements within the bed. MAY,[35] as noted above, also used radioactive tracers for solids diffusion studies and helium tracer gas for "cross flow" assessments.

PARKER and STEVENS[33] attempted to assess the effect of interparticle forces in a gas fluidized system by injecting quantities of water vapour into the bed and assessing the degree of segregation from the change in bed expansion from the dry system. Since it seems unlikely that electrostatic or other interparticle forces generally have a dominating effect on uniformity of bed behaviour, this study is of most value for operations where it is necessary to inject liquid into a gas fluidized bed.

CAIRNS and PRAUSNITZ[8] observed the variation in velocity profile through the centre of a liquid fluidized bed as a function of liquid velocity. They then extended the study[9] to embrace longitudinal mixing. The longitudinal eddy diffusivity was found to increase with particle density and was markedly dependent on the velocity profile. The mixing results are consistent with the fact that the fluidized bed may be considered as a transition between a packed bed and an open tube. SLIS *et al.*[44] have studied the propagation of a disturbance in voidage through a liquid fluidized system. Their proposed mechanism agreed with their observations.

LOEFFLER and RUTH[31] propose an empirical equation as a "theory" of fluidization and sedimentation. In this, the terms are combined in such a manner that the STOKES relation is obtained for a single particle and the KOZENY relation for a packed bed. Comparison of their results from sedimentation and fluidization experiments show that a given degree of porosity is reached at slightly lower Reynolds number for sedimentation than for fluidization. This suggests that flow resistance is greater with sedimentation than for fluidization.

Elutriation and Pneumatic Conveying

THOMAS *et al.*[46, 47] have studied the effect of particle size distribution on classification and elutriation in gas fluidized systems. A definite size concentration gradient was observed between the centre and wall of the bed. It became more pronounced when working with beds 3 ft deep and was dependent on the initial fines concentration. Further work is necessary to establish a correlation between the fines concentration, bed height, gas velocity and initial fines concentration. They found that an exponential relationship between solids elutriation and gas velocity was only applicable when perfect bed mixing obtained. The rate of elutriation may be expected to depend on the fines concentration near the top of the bed and to be affected by the loss of fines from the bed. Accordingly, they proposed an elutriation correlation, more complicated than that suggested by LEVA, which included the segregation tendency and which was therefore more successful at the beginning of the elutriation period. The importance of this stems from the fact that an operating bed may be maintained in such a condition.

ANDREWS has attempted[1] to predict, from measurable bed variables, the number of particles with suitable velocity vector to escape from the bed surface. He was able to estimate an entrainment rate constant according to experimental conditions; it having a unique value for pneumatic transfer. The author claims that it should be possible to predict entrainment from transfer line experiments. PRICE *et al.* have suggested that there is a single relationship between hold-up and slip velocity for any vertical fluidized system whether liquid or gas, co- or counter-flow. Their more recent paper[40] confirmed this in application to liquid/solid systems operating under counter-flow condition. The hold-up or pressure drop in a vertically moving fluidized

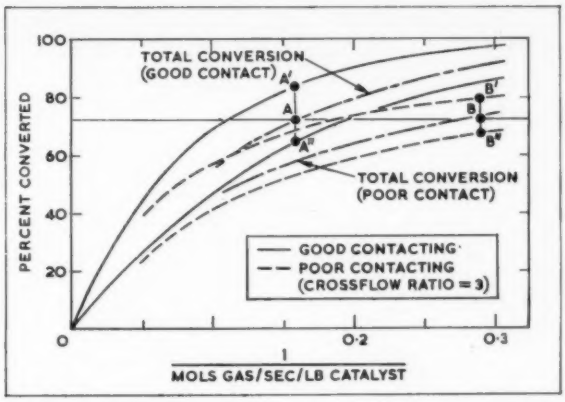

Fig. 2. Two first-order reactions with different rate constants: contacting affects selectivity.

system can be estimated as a function of fluid velocity with solids velocity as a parameter from a batch experiment. In a further extension of this work, HOFFMAN *et al.*[23] have tested predictions for systems having a range of particle size.

From a study covering the transition from continuous fluidization to pneumatic conveying, GOPICHAND *et al.*[20] observed that the pressure drop at transition was dependent on the physical properties of the solid and dimensions of the fluidizer. The bed density may be predicted empirically for a known solids feed rate or gas velocity. Some empirical equations have been suggested for horizontal fluidized solids transport.[51] Such a system has a higher capacity than the usual pneumatic system, but it is doubtful how far the correlations between particle velocity and overall pressure drop is applicable. Surprisingly, particle size and shape had little apparent influence on flow characteristics.

The advantages of fluidized methods of bulk handling and mixing have been described by D'ARCY SMITH.[45]

Experience from fluidized systems has been applied to hold up problems of interphase contacting in liquid/liquid systems.[50]

Heat and Mass Transfer in Fluidized Systems

The chief problem facing the experimenter in this field is that of measuring pertinent factors. The high degree of homogeneity in a well-mixed bed makes it exceedingly difficult to measure the relevant thermal and concentration gradients. The reviews by BANNISTER[4, 5] show how diverse are the published estimates of heat transfer properties. This is largely due to the fact that results are so often characteristic of the equipment.

VREEDENBERG[40] proposed a correlation for heat transfer between a vertical tube and surrounding fluidized bed which was further modified by an additional factor when the inertial effects of heavier particles have importance. Generally it gives better predictions than WENDER and COOPER'S correlation.[52] LEVA and WEN[29] have commented on the inability of the WENDER and COOPER correlation to include Van Heerden's results. They suggested that this was due to the omission of an adequate functional relationship between fluid mass velocity and bed expansion in the correlation. WENDER and COOPER[53] admitted discrepancies, but suggested that they were more likely due to the low bed depth to diameter ratio used by Van Heerden compared with the other workers. Again the problem of equipment characteristics.

RICHARDSON and AYERS[41] studied heat transfer between hot gas and particles in a very shallow fluidized bed. By refined thermocouple techniques they were able to measure temperature gradients in a zone less than $\frac{1}{10}$ in. deep. By

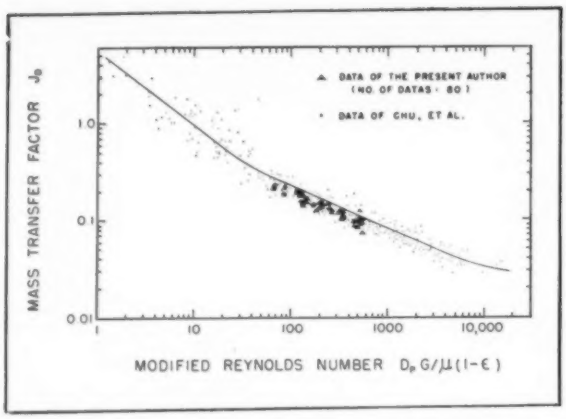

Fig. 3. Generalized correlation of mass transfer data.

this they demonstrated that there was no temperature gradient in the gas beyond the first shallow zone at the entrance to the bed. For Reynolds numbers between 0.5 and 35, the results were correlated by the equation:

$$Nu = 0.054\,Re^{1.28}$$

They suggested a mechanism whereby heat was transferred initially from the hot gas to a thin film of gas round each particle, which subsequently gave up part of its heat to the particle and the remainder was returned to the bulk of the gas. GARNER *et al.*[16] studied the characteristics of a stirred and fluidized annular heat exchanger. Overall heat transfer coefficients were dependent on the residence times of the particles at the heat transfer surface. The analysis of these preliminary results showed an apparent reduction in the resistance to heat transfer as the bed became fluidized or, from subsequent experiments, was vigorously stirred without fluidization. It was concluded that the high overall heat transfer coefficient was also largely due to the localization of the temperature gradient in a narrow zone adjacent to the heat transfer surfaces, thereby maintaining the maximum driving potential. Experiments performed under high vacuum confirmed that particle/heat transfer surface and interparticle contacts are so small that negligible heat was transferred without the gas to act as a heat transfer medium.

The mass transfer coefficient in a given system has been observed to depend on the overall bed expansion in a liquid fluidized system.[14, 15] In the experiments reported a log mean driving force was assumed, but this is obviously peculiarly dependent on the geometry and other properties of the system, as with heat transfer systems. Mass transfer coefficients obtained for the restrained fluidized bed were intermediate between those for a uniformly compressed fluidized bed and a uniformly expanded bed. This offers a means of adjusting the overall coefficient according to requirements. Similarly, a restrained fluidized bed may also be a means of regulating overall heat transfer.

Variation in the effective mass transfer coefficient with fluidizing conditions (including bubbling) have been reported for the gaseous system where cumene is cracked over a catalyst.[19]

Industrial Applications

Many of the industrial applications more recently described belong to the field of metallurgy. HAWTHORN *et al.*[22] describe many details of the production of uranium tetrafluoride from the nitrate in a fluidized bed. This utilizes the good heat transfer and solids handling properties of the bed. At present operated batchwise in order to obtain adequate conversion, it is hoped that it will be possible to operate the three stages of the process continuously when more experience has been acquired and residence time problems solved. Concentrated uranyl nitrate is injected into the first reactor and it represents a considerable degree of achievement that a fluidized bed can be maintained under such conditions. Since uranium is a dense material, relatively high pressure drops occur across the bed which make bed behaviour generally less stable. Use of a slightly tapered column[30] ($\frac{1}{4}°$) to give a constant velocity profile up through the bed has been found to increase operational stability; the consequent reduction in bubbling reduces reagent bypassing. Uranium dioxide has been coated with metallic tungsten in a partial tungsten hexachloride atmosphere.[17] Here vibration was found to assist maintenance of uniform fluidizing conditions.

The patents relevant to fluidized reactor design for naphthalene oxidation have been reviewed by RILEY.[42] To solve the problem of catalyst agglomeration but yet still to retain the good heat transfer characteristics of a fluidized bed for the oxidation of ethylene, fixed silver-coated catalyst strips were inserted in a fluidized bed of inert material.[12] Adequate temperature control was achieved on the experimental scale. It is not known how readily such a reactor may be "scaled up". Details of two desulphurising processes have been published recently.[6, 21] Fluidized systems have also been developed for mist removal from a process stream[43] and as an efficient absorber for a noxious vapour[39] (absorption of UF_6 on a bed of UF_4).

Spouting Beds

The techniques of spouting beds are closely allied to those of general fluidization and are particularly applicable when dealing with a material of cylindrical rather than spherical shape (certain crystalline materials and, in the agricultural field, grains) which would not fluidize stably. THORLEY *et al.*[48] give a full analysis of the behaviour of a spouted wheat bed. Attempts to correlate the general spouting bed pressure drop/gas-flow behaviour with that of packed beds were not successful, but it was possible to predict the maximum spoutable bed height. In general, the maximum pressure drop with a spouting bed was approximately two-thirds of the pressure drop due to the weight of the bed. An empirical correlation accurate to within 15 per cent has been developed for prediction of the minimum spouting velocity. The main variables were the air flow and column size; solids circulation increases with air flow. The cone angle and orifice size had an effect on the cross flow of the solids into the spout, but little effect on the total amount of solids circulation. MADONNA and LAMA[32] give a correlation between pressure drop (including the pressure drop across the orifice) and flow to the spouting bed. In a further paper MADONNA *et al.*[33] reviewed the whole field of spouting beds and attempted to show that their correlation for pressure drop was of the same form as that previously derived by THORLEY, MATHUR, GLASSEN and GISHLER. This it would be only if a function which they introduced should take the form to make it so.

LIANG TSENG FAN and SWARTZ[13] showed that a correlation proposed by LEVA for the prediction of the onset of fluidization may be used for the prediction of the minimum spouting velocity if the effective diameter for insertion in the correlation was estimated as the square root of the minimum cross-sectional area through the grain.

GHOSH and OSBERG[18] report experimental studies of heat transfer in water spouted beds. At the same water flow rates, the spouted bed gave a lower rate than the fixed bed, because a large fraction of the water by-passed the wall region and flowed up the spout. In the turbulent region at the top of the spout, the heat transfer rate was increased.

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The Operation and Maintenance of Calder Hall Type Reactors*

The Institution of Chemical Engineers (North Western Branch), 16th Annual General Meeting

U.K.A.E.A. CALDER Hall type reactors operate on the production of plutonium with electricity as the by-product. There are eight reactors, four at Calder Hall Nuclear Power Station and four at Chapelcross Nuclear Power Station. The first was commissioned in 1956 at Calder Hall and the last in 1959 at Chapelcross.

Each reactor is charged with 130 tons of natural uranium in a core of 1100 tons of graphite. Heat from the nuclear fission process is removed, by circulating 25 tons of CO_2 gas at 100 psi, and transmitted to four steam-raising units. Steam is taken off these units at two pressures and is fed to two turbines with high and low steam checks.

The design thermal output for each reactor was 180 MW with a gross electrical generation of 42 MW. Modifications during these four years have increased the output to 220 MW and the electrical generation to 47 MW. Further modification should increase the electrical generation to 52 MW per reactor.

Total electrical units sent out from Calder Hall during 1959/60 represent 11.3 per cent of the electricity disposed of by the North Western Electricity Board. The Chapelcross reactors supplied 20-59 per cent of the electricity sent out by the South of Scotland Electricity Board during the same period.

Operation

These reactors have to be shut down for fuel changing. The overall station efficiency depends on (a) the day-to-day efficiency for maximum plutonium and electricity production; (b) the long-term efficiency of the system; and (c) the fuel changing cycle.

The maintenance of high day-to-day efficiency depends on the enthusiasm and vigilance of the man-power on the operating floor. Many of the shift controllers are former Merchant Navy engineering officers and this training seems to be an excellent foundation for their job, particularly in the meticulous attention to detail.

Long-term efficiency arises because the method of operation of these reactors is essentially a batch process with a charge life of months or years. During the irradiation period, the conditions within the reactor are continually changing and high long-term efficiency depends on the good liaison between the operators and the technical or development staffs.

Changing fuel efficiently presents major planning and handling problems. 130 tons of irradiated uranium, in the form of about 10,000 individual fuel elements, has to be removed from the reactor core in heavy shielded containers, and replaced by unirradiated elements. Shut-down periods for refuelling have been steadily reduced from 80 days in 1957 to less than 3 weeks at present.

Maintenance

A large proportion of ancillary plant can be maintained while the reactor is operating on full power. Some items of plant, namely the gas circulator drives (2200 hp), and electrical generators can be maintained with some loss of production. Maintenance to the gas pressure circuits is carried out during shut-down for major refuelling.

Conclusion

Experience during the 18 years of operation with these reactors has shown that these first prototype reactors may now be justly considered to have taken their place in modern industry and they are making a marked contribution to power supplies in England and Scotland. Their safe operation is well within the capabilities of good industrial management, and the U.K.A.E.A. has confidence in the nuclear reactor for electricity generation.

* From an address given by MR. K. B. ROSS at The Institution of Chemical Engineers (North Western Branch) 16th Annual General Meeting, 1961, on Friday, 10th March, 1961, at Midland Hotel, Manchester.

Fig. 1. A multi-layer pressure vessel seen against the background of the Soviet Pavilion. This vessel (VEB Gemania Karl Marx Stadt) is 1 m i.d. and 18 m in length. Operating pressure and temperature are 325 kp/cm² and 380°C respectively.

LEIPZIG SPRING FAIR 1961

THE Leipzig Spring Fair can usually be counted upon to provide the visitor with plenty that is novel and interesting, whether his particular interests lie in one of the many branches of technology, in large contracts, or in discussions on business relations between states of differing economic structures; and after the rigours of the Fair itself—it is often congested—it is always possible to find relaxation through the many varied artistic entertainments offered at Fair time in Leipzig itself—a traditional centre of culture.

Larger British Representation

It was interesting to see how much greater British representation was compared with last year, in terms both of area covered and of numbers represented. In fact, floor space occupied was double that of last year and the number of exhibitors increased from some 150 to 200. Among the British exhibitors were several firms with a strong interest in processing equipment and chemical engineering and, in a sense, these firms represented almost the entire field of hardware and services required for a chemical project. At one end of the scale were to be found Humphreys & Glasgow who, with Petrocarbon Developments Ltd., offered complete plants, and who are jointly responsible for an ethylene and benzene unit now under construction at the Leuna works; next came Apex Engineering Ltd., whose display —sold out, incidentally, during the Fair—included a variety of unit operation and process equipment. There were to be found such firms as G. A. Harvey, whose fabricating skill and mechanical design experience are being drawn upon in the construction of the Leuna plant, and Colville's of Glasgow, who, with examples of their stainless-steel clad (Colclad) plates, represented metallic materials of construction. At the other end of the scale a number of firms displayed automatic control equipment, and ancillaries such as valves and pumps.

Business Results at British Stands

Judging from early reports, business results were impressive. Apex, as already mentioned, disposed of all their display equipment, including two Y-cone blenders, a cutter mill for size reduction of plastics and fibrous materials and a comminuting mill.

In the instrumentation field Solartron Electronic Group Ltd. disposed of much of the equipment shown on their stand, although not all of this was for process control purposes. Hilger & Watts were another to dispose of their display and, with contracts, their sales amounted to £24,000. Oxley Engineering, who showed examples of stainless-steel equipment, received many enquiries, including several from Russia, Poland and Hungary, a proportion of which is expected to lead to orders. Rank Precision, makers of industrial television equipment, were yet another firm to sell their entire display.

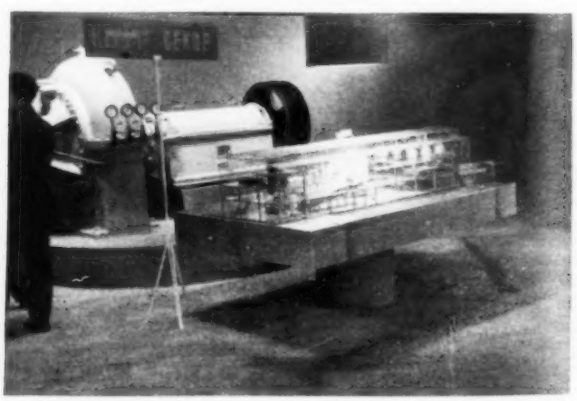
Special valves shown by Limitorque, complete with electrically-operated actuators, were often a centre of attraction and many encouraging enquiries were received at this stand. Some were of a highly novel character so far as the application of this type of equipment is concerned.

One of the most important contracts concluded at the Fair was obtained by Wycon Services Ltd. for the supply of two complete plants to the Soviet Union, one for the manufacture of herbicides and the other for textile treatment chemicals. The possibility of contracts of similar magnitude which may be concluded with other Eastern European countries as a result of participation in the Fair is not ruled out.

In addition to equipment there were many displays of scientific books and journals, and the sole British exhibitor in this field, the Pergamon Press, sold its entire exhibit including a sizeable proportion of books on chemical engineering and related fields.

Fig. 2. A view of the Apex Construction Co.'s section of the combined British stand. The equipment shown by this company was sold during the Fair.

Fig. 3. A model of a complete sugar factory offered by the Polish organization Cekop. In the background, a large rubber-lined pump.



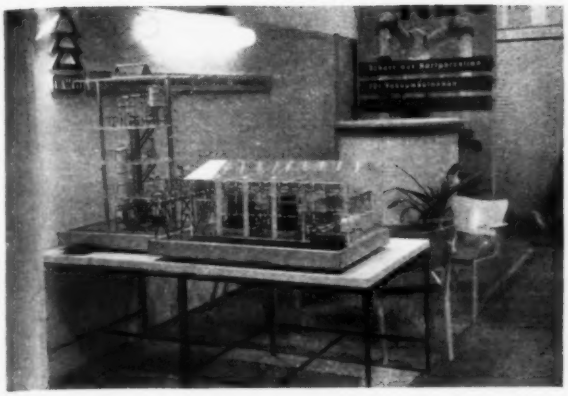


Fig. 4. A view of a model of a complete plant in chemical porcelain shown by VEB Keramische Werke Hermsdorf. This Company showed a number of new pieces of equipment.

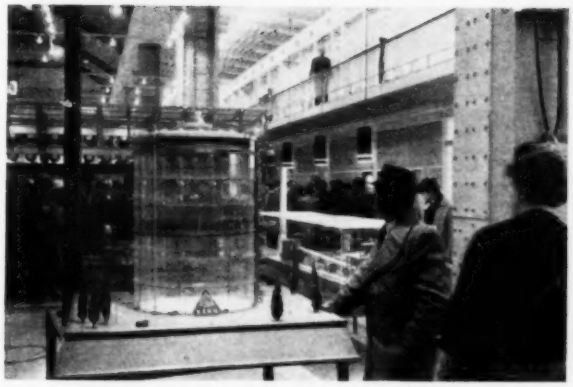


Fig. 5. A scene in the Czech Pavilion. Centre: model of a gas storage vessel. To right: a cement kiln model; background, a new synthetic fibre spinning machine

Chemical Manufacturers Present in Force

Chemical manufacturers were strongly represented, prominent among them being such firms as Chemische Werke Hüls A.G. VEB Chemische Werke Buna, BX Plastics Ltd., Badische Anilin Soda Fabrik, I.C.I. Ltd. (Heavy Chemicals, Plastics and Dyestuffs Divisions), Kuhlmann Ets., Pechiney Saint Gobain, VEB Leuna-Werke "Walter Ulbricht", E. Merck A.G., Degussa and many others. These various exhibits attracted considerable attention and, in many cases, led to worth-while business; for example, the I.C.I. Dyestuffs Division obtained contracts to the tune of £150,000 with the East German authorities for various dyes required by the printing inks industry.

Conferences and Discussions

It is common for International Fairs of this kind to be accompanied by conferences and discussions. These provide information about orders and contracts obtained during the Fair, provide a certain amount of technical information and frequently deal with trading problems of the kind which arise during the course of East-West trade. Such an event was a meeting arranged by the East German Ministry of Foreign and Inter-German Trade between exhibitors, businessmen and visitors from West Germany and West Berlin, including representatives of the chemical industry of West Germany, on the one hand, and officials of the above Ministry on the other. This meeting took place in a cordial although frank atmosphere, and it is significant that several speakers from West Germany spoke out in favour of simpler inter-German trade procedures, and for the removal of a number of discriminatory measures which they stated had been imposed by their Government. The interest aroused by this meeting may be gauged by its attendance of 500 West German visitors. An intensive exchange of views between West German businessmen and prospective buyers in East Germany, took place, and there is little doubt that this and similar events at the Fair have led to greater confidence on the part of West Germans in their dealings with East Germany.

The Fair has underlined the excellent prospects for the trade between British firms and East Germany, where British engineering capabilities are well appreciated and respected. What is surprising is the apparent disregard of these prospects by officialdom, a typical example being the refusal to grant credits for £35 million worth of rolling mill equipment to an East German enterprise—more surprising in view of the deteriorating balance of payments situation facing Britain.

Extent of Exhibits

Among other participants at the Fair, Poland—showing chemical and processing plant in quantity for the first time—increased the area of its display by some 50 per cent, Czechoslovakia took 97,000 sq ft, the Soviet Union 130,000 sq ft and East Germany something like a million sq ft. Of other countries, the biggest exhibitor was undoubtedly West Germany, including West Berlin, with an occupied space of 350,000 sq ft. This representation would have undoubtedly been far greater had it not been for the East-West trouble which arose last year at a time when some 1500 West German firms had already booked space totalling more than 500,000 sq ft. The West German Government's attitude to the Fair led to something like a thousand West German firms cancelling their space; when the situation had eased it was too late for them to recoup the cancelled space, which had meanwhile been booked by exhibitors from other countries.

The exhibits falling within the sphere of interest of this Journal ranged from offers of complete plants, through various types of ancillary equipment, to publications on chemical engineering. *To be continued*

Fig. 6. A model of a complete fibre board plant offered by the Czech organization, Technoexport.

Fig. 7. A view of valves shown on the VEB Armaturen Werke Reichenbach stand. In the background, centre, the carbonating tower of a soda factory.

Abstracts

GROUP A — FLUID DYNAMICS

Determination of the Effectiveness of Mixing by Turbine Mixers

A survey of the literature dealing with the effectiveness of mixers. The paper discusses the performance of open and closed turbine mixers used in three geometrically similar systems. Tests were carried out on mixtures of water and mineral oil (ratio 4:1) in baffled and non-baffled tanks. Results of measurements of the homogeneity of the mix are presented diagrammatically for each type of mixer operating with and without baffles. Below a certain value of a mathematical criterion for representing the effectiveness of mixing, a turbine with baffles was found to be the most effective type of mixer. 10 graphs, 4 diagrams of equipment details and 14 refs.

H. Blasinski, *Przem. Chem.*, 1960, **39** (12), 768-73.

Agitation of Viscous Newtonian and Non-Newtonian Fluids

This paper presents data for fluids agitated by multiple impellers in vessels only slightly larger than the impeller. At a given level of mixing rate, the large decreases in power requirements which are possible by the use of low tank diameter, impeller diameter ratios and/or two impellers have been quantitatively studied. Marine propellers, fan turbines and flat-bladed turbines were used under a range of conditions. 17 refs.

A. B. Metzner *et al.*, *A.I.Ch.E.J.*, 1961, **7** (1), 3-9.

Drag Coefficients at Low Reynolds Numbers for Flow Past Immersed Bodies

Drag coefficients were determined at low N_{Re} for cylinders ($0.1 \leqq N_{Re} \leqq 1.0$) and flat plates ($0.05 \leqq N_{Re} \leqq 2.0$) moving through a viscous medium and found to be inversely proportional to N_{Re} for all bodies studied. The data were analysed to obtain a relationship between drag coefficients and N_{Re}.

The diameter of the tank containing the viscous fluid had a very definite effect upon the drag coefficient of the cylinders and plates studied.

For flat plates in perpendicular flow, the plate width/plate length ratio had no effect in the range studied. The tank diameter had a considerable effect. 17 refs.

A. M. Jones and J. G. Knudsen, *A.I.Ch.E.J.*, 1961, **7** (1), 20-5.

Combined Free and Forced Convection in a Constant-temperature Horizontal Tube

This paper reports an experimental study of superposed free and forced convection for air in a horizontal tube. The laminar Nusselt number ranged from 29.9 to 15.2; the laminar flow Graetz number ranged from 33 to 1300; and the Grashof-Prandtl modulus, based on properties of air at the wall temperature, ranged from 1.1×10^6 to 2.2×10^6. An analysis of the system from a macroscopic viewpoint led to the determination of an equation which fits the laminar flow experimental data in the range of Graetz numbers 60 to 1300. An equation is also presented for the turbulent data. 9 refs.

T. W. Jackson *et al.*, *A.I.Ch.E.J.*, 1961, **7** (1), 38-41.

Turbulent Newtonian Flow in Annuli

The paper presents a Prandtl mixing length approach to give a friction factor vs N_{Re} expression for annuli, which describes tube flow and slit flow as special cases. This expression predicts friction factors within the accuracy of experimental data; it is more accurate than the usual hydraulic-radius procedure and of comparative accuracy to other recent annulus friction-factor treatments. 23 refs.

D. M. Meter and R. B. Bird, *A.I.Ch.E.J.*, 1961, **7** (1), 41-5.

A Modification of the Momentum Transport Hypothesis

A continuous velocity distribution is derived which is based on an arbitrary modification of Prandtl's mixing length expression. The resulting velocity distribution agrees well with experiments for transition and fully developed turbulent flow throughout the entire cross-section of the conduit. Furthermore, the mixing length expression applies to parallel flow in smooth circular tubes and between infinite parallel plates with the same set of constants. 15 refs.

W. N. Gill and M. Scher, *A.I.Ch.E.J.*, 1961, **7** (1), 61-3.

The Extension of Couette Flow Solution to Non-Newtonian Fluids

Couette flow is flow between two parallel plates, one of which is stationary and the other moving at constant velocity U. A prescribed thermal condition is imposed on these two plates. The paper shows that the solution of a Couette flow problem in laminar heat transfer for Newtonian fluids can also be applied to the case of non-Newtonian fluids, provided that the relevant parameters are properly defined. 1 ref.

Chi Tien, *Can. J. Ch. E.*, 1961, **39** (1), 45.

Drag Forces in a Hydraulic Model of a Fluidized Bed—Part I

The paper describes experiments carried out to measure the drag on a sphere ($\frac{1}{2}$ in. to $\frac{3}{8}$ in. dia.) in a water stream (Reynolds No. 10-1000) and the effect which neighbouring spheres had on the drag. The drag on a sphere in a packed array is about twice that on a similar isolated sphere. Adjacent particles repel one another but, when spheres are in line, they reduce the drag on one another.

Some of the features of fluidized beds are explained, but further knowledge of the gas flow patterns is needed before these results can be applied to bubble formation in gas fluidized beds.

P. N. Rowe and G. A. Henwood, *Trans. Inst. Ch. E.*, 1961, **39** (1), 43.

Flow Through and Blockage of Capillary Leaks

The various types of gas flow that can occur through small-bore capillaries are treated in this paper to help in understanding the behaviour of small leaks in vacuum equipment. Some formulæ are derived that represent flow rates under different conditions. Some causes of capillary blockage, such as surface tension, surface adhesion and viscosity, are investigated and the elimination of such blockage, by pressure and evaporation, is discussed.

G. Burrows, *Trans. Inst. Ch. E.*, 1961, **39** (1), 55.

The Horizontal Pipeline Flow of Equal-density Oil-water Mixtures

The horizontal flow of oil-water mixtures of equal density was investigated in a 1-in. laboratory pipeline. Oils of viscosities 6.29, 16.8 and 65.0 centipoises were used. Superficial oil velocity ranged from 0.05 to 3.0 ft/sec and superficial water velocity from 0.1 to 3.5 ft/sec; input oil-water ratios ranged from 0.1 to 10.0.

The flow patterns obtained for each oil were similar and largely independent of the oil viscosity. At high oil-water ratios, oil formed the continuous phase and a water-drops-in-oil régime was noted. As the oil-water ratio was decreased, a gradual change of pattern occurred to an oil-drops-in-water pattern, in which water was the continuous phase.

The most viscous oil exhibited anomalous behaviour at low superficial water velocities.

The pressure drops were reduced to a minimum by the addition of water, provided that the oil was not in turbulent flow. 11 refs.

M. E. Charles, G. W. Govier and G. W. Hodgson, *Can. J. Ch. E.*, 1961, **39** (1), 27-36.

GROUP B — HEAT TRANSFER

A Method of Measuring Thermal Diffusivities of Rocks at Elevated Temperatures

This method involves heating cylindrical test pieces at a constant rate of rise of the edge temperature, and measuring the temperature difference between a point just inside the sample edge and the centre of the test piece. In these tests, thermal diffusivity was inversely proportional to the temperature differential. Measurements were reproducible within ±10 per cent. 15 refs.

W. H. Somerton and G. D. Boozer, *A.I.Ch.E.J.*, 1961, **7** (1), 87-90.

Brit. Chem. Eng. Abstracts: **FOLIO No. 5**

Heat Transfer in a Chemically Reacting System (N_2O_4-NO_2)

This paper discusses an analytical investigation on the effect of chemical reaction on heat transfer for the dissociating system $N_2O_4 \rightleftharpoons 2NO_2$ in turbulent pipe flow. 18 refs.

J. P. Irving and J. M. Smith, *A.I.Ch.E.J.*, 1961, **7** (1), 91-6.

The Effect of Acoustic Vibration on Forced Convective Heat Transfer

Sound at resonant frequencies of 198, 256 and 322 c/sec, as well as non-resonant frequencies, was imposed on air flowing at N_{Re} 560 to 5900 in the core of a horizontal, double-pipe, steam to air heat exchanger. Acoustic vibrations have improved the rate of forced convective heat transfer, increasing the N_{Nu} up to 51 per cent in the laminar region and 27 per cent in the turbulent region. Improvement increases sharply at resonance and generally increases with both amplitude and frequency. Improvement is greater below N_{Re} 2100 than above. The results are correlated.

R. Lemlich and C. K. Hwu, *A.I.Ch.E.J.*, 1961, **7** (1), 102-6.

Simultaneous Mass and Heat Transfer in the Flow of Gases Past Single Spheres

Mass and heat transfer factors were simultaneously determined from the evaporation of water and nitro benzene in air from Celite spheres. The results, $j_d = \frac{0.33}{N_{Re}^{0.40}}$ for mass transfer and $j_h = \frac{0.35}{N_{Re}^{0.40}}$ for heat transfer, indicate that the processes of mass and heat transfer for the flow of air past single spheres are directly related. 10 refs.

S. Evnochides and G. Thodos, *A.I.Ch.E.J.*, 1961, **7** (1), 79-80.

Experimental Investigation in Heat and Mass Transfer

The results of two major investigations in heat and mass transfer are summarized. (a) Heat transfer between a vertical tube and a sprayed film was measured and the mechanism of heat transfer was, to a great extent, explained. (b) Work drying under the impact of a warm air current was investigated. The determinant mass transfer coefficients in the first drying section were determined. A clear relationship was obtained between the Nusselt number of the mass transfer, the Schmidt number, the Reynolds number and the main linear dimensions. Further, the critical Reynolds number, at which the boundary layer becomes turbulent, was evaluated. 14 refs.

H. Glaser, *Chemie Ing. Tech.*, 1961, **33** (3), 146-55.

The Influence of Gas Liberation on Heat Transfer in the Heating of Liquids

This experiment deals with the liberation of air from water as the temperature is raised. Dissolved air separates in the heated boundary layer and increases the heat exchange, since the boundary layer is destroyed by the formation of air bubbles. The air separation creates different effects depending on the arrangement of the heat exchange tube (horizontal or vertical) and the direction of flow of water (upwards or downwards). Results in a horizontal and vertical double-tube heat exchanger show an increase in heat exchange of up to 15 per cent in the transition region between laminar and turbulent flow. 11 refs.

B. Metais, *Chemie Ing. Tech.*, 1961, **33** (3), 182-4.

Heat and Mass Transfer with Flow Over or Through Bodies of Different Geometrical Shapes

The paper presents a variety of investigations on the heat and mass transfer between flowing media and bodies of different shape and arrangement. The purpose was to obtain reliable predictions of the behaviour of individual bodies of such shapes as occur in material to be dried or in packings. The results are applicable to conditions of constant surface temperature or concentration and they can be represented in a generalized dimensionless form, if suitably chosen definitions are introduced for a characteristic length, average velocity, hydraulic diameter and temperature or concentration difference. 19 refs.

O. Krischer, *Chemie Ing. Tech.*, 1961, **33** (3), 155-62.

Ceramic Heat Exchangers for High-temperature Heat Transfer from Helium

The paper describes research undertaken to develop a ceramic heat exchanger, operating at high temperature, for utilizing nuclear heat from gas-cooled process heat reactors. Heat transfer from helium flowing through a single tube vitreous alumina heat exchanger was studied. Inside film coefficients were determined at mean surface temperature of 200-1570°F, inlet gas temperature of 1450-2665°F, and N_{Re} up to 560. The gas: surface temperature ratio was varied from 1.05 to 7.6.

Ceramic heat exchangers are suitable for high temperatures, but are limited to low pressures. Their use depends on developing reliable gas-tight seals and eliminating high thermal stresses. 21 refs.

S. G. Browning and J. J. S. Sebastian, *Ind. Eng. Chem.*, 1961, **53** (3), 191-6.

Approximate Solutions of Conduction of Heat Through Non-homogeneous Media

An approximate analogy is established by comparing the respective difference equations of heat conduction through a homogeneous and non-homogeneous medium. This gives a solution of conduction through a non-homogeneous medium in terms of the known solution for homogeneous cases.

An example is given in which the approximate solution gives a higher result (about 10 per cent), but the time saved in computation is quite significant. This method may be useful for some preliminary engineering calculations. 2 refs.

Chi Tien, *Can. J. Ch. E.*, 1961, **39** (1), 42-4.

Simultaneous Heat and Mass Transfer in Free Convection

This is a theoretical investigation into simultaneous heat and mass transfer, in laminar-free convection, from a vertical flat plate. 10 refs.

W. R. Wilcox, *Ch. E. Sci.*, 1961, **13** (3), 113-19.

Heat Transfer to Reacting Systems: Heat Transfer to N_2O_4 Gas Flowing Normal to a Heated Cylinder

Rates of forced-convective heat transfer from a cylinder to N_2O_4-NO_2 gas at 1 atm were experimentally determined at free stream velocities up to about 40 ft/sec.

The high thermal conductivity of this system gives it heat transfer coefficients, based on a temperature driving force, up to 8 times greater than those for a similar non-reacting system. 16 refs.

J. L. Richardson *et al.*, *Ch. E. Sci.*, 1961, **13** (3), 130-41.

Heat and Mass Transfer in the Presence of an Inert Gas

The paper describes a new graphical method, for solving enthalpy transfer problems, in which a modified enthalpy is the transfer potential, and illustrates its use by its application on the tetrachloroethylene-air system. The use of this graphical method in the design of a cooler-condenser is described. 13 refs.

H. F. Johnstone and W. B. Retallick, *Ch. E. Sci.*, 1961, **13** (3), 155-66.

Drying Wheat in a Spouted Bed

Continuous drying of wheat in a spouted bed approximates the drying of uniform, spherical, solid particles in a well-mixed, isothermal bed, with the drying rate controlled by moisture diffusion within the particles, and the diffusion coefficient independent of concentration. This paper presents a mathematical solution which was developed for this general problem.

Diffusion coefficients calculated by this method agree closely with established values. Correlations are presented which facilitate the prediction of drying rates, energy requirements, safe and economical limits of operation for spouted wheat dryers. 17 refs.

H. A. Becker and H. R. Sallans, *Ch. E. Sci.*, 1961, **13** (3), 97-112.

GROUP C — MASS TRANSFER

A Survey of Methods of Calculating the Equilibria of Absorption Processes

Methods are described for the determination of absorption equilibria in systems where a gaseous component occurs at a temperature above the critical. There is a discussion of the conditions in which Henry's law applies, the methods for the computation of equilibria from the physico-chemical data of components, and their extrapolation to different conditions of pressure and temperature. The solubility of gaseous mixtures, gases in liquid solutions, and an example of non-isothermic absorption are also described. A diagram, tables facilitating the computation, and an example of an equilibrium calculation are given. 39 refs.

J. Ciborowski and R. Pohorecki, *Przem. Chem.*, 1960, **39** (12), 759-62.

Fluid Particle Mass Transfer in a Packed Bed

Mass transfer coefficients have been measured for air flowing through naphthalene pellets (spherical and cylindrical) in a bed 4 in. dia. packed 5 in. to 10 in. deep.

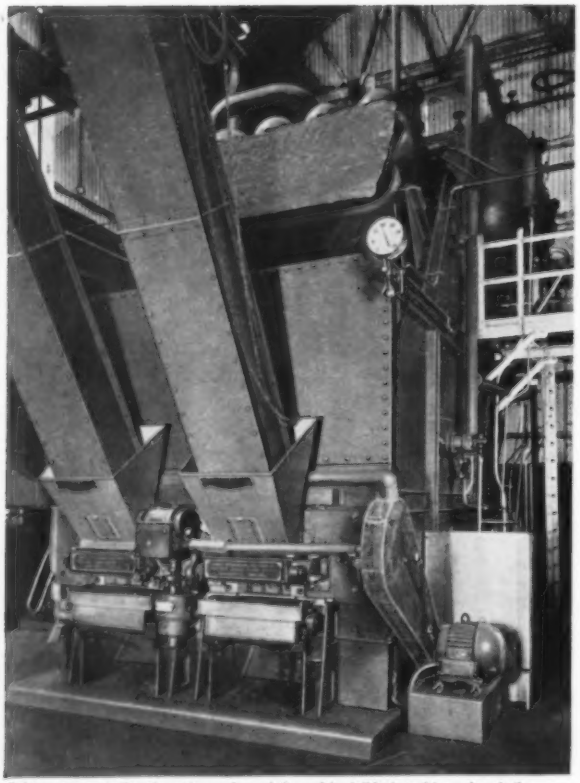
Radial concentration profiles were obtained for some conditions, from which the radial variation of the mass transfer coefficient was determined. The point values of kg follow an equation $kg = aG^b$. Values of kg and j_a have been obtained, for all the pellet sizes, as functions of mass velocity and N_{Re}, respectively, from mixed outlet concentrations. 32 refs.

R. D. Bradshaw and C. O. Bennett, *A.I.Ch.E.J.*, 1961, **7** (1), 48-52.

Brit. Chem. Eng. Abstracts: **FOLIO No. 6**

BCE 9588 for further information

COAL—properly used—is the cheapest fuel for the Chemical Industry



Coking stokers feed coal continuously, quietly and invisibly into this modern boiler.

Search the industrial scene—and it is difficult to find any major industry that does not use chemicals. But even in the prospering chemical and chemical processing world, sound economics are of primary importance and wise managements will always make every possible saving and every possible improvement that will help keep prices stable while satisfying—and expanding—their home and overseas markets.

BEGIN AT THE BEGINNING—THE BOILERHOUSE

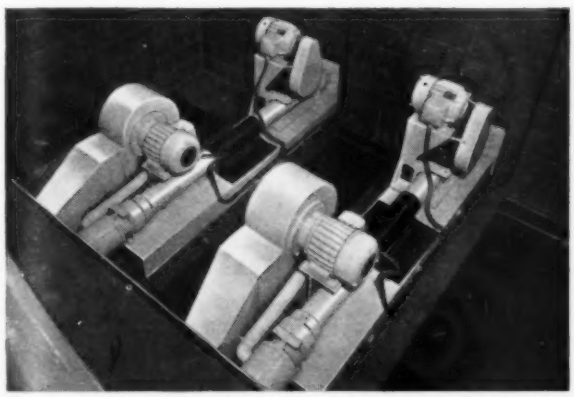
There are still some chemical plants that handicap their finances with outdated boilerhouses. To modernise other machinery while 'making-do' with inefficient boilers is to throw good money down the drain. Modern coal-burning installations can be so efficient that they will more than pay for themselves in a remarkably short time. They are, without question, the *first* essential in a chemical plant that is going to make rising profits for its management.

COAL IS THE RELIABLE FUEL

One question for any long-term planning is obvious: can supplies of coal be guaranteed? The answer is yes—without qualification. The mining industry—Britain's *largest single industry* is becoming increasingly efficient; its equipment is the best of its kind. And British coalfields contain enough coal to supply every industrial demand for centuries to come.

COAL IS CLEANER, HOTTER

Modern grading and washing methods ensure that coal is the most efficient and consistent fuel for every type of boiler—the ideal fuel for every section of the chemical and chemical processing industry. But to obtain the maximum heat at the lowest cost, coal should be mechanically stoked. A mechanical stoker automatically feeds the right amount of coal for the boiler load even when the load is varying; it burns coal at optimum efficiency all the time without the emission of smoke; and it virtually replaces the human element in boiler operation. There are many types of mechanical stokers, of which the most commonly used are the Chain Grate stoker, the Coking stoker, the Underfeed stoker and the Sprinkler stoker. Standard models are available for all sizes of boiler.



Two underfeed stokers feeding coal direct from a storage hopper into a modern vertical boiler.

OVER 80% OF BRITISH INDUSTRY USES COAL

The National Coal Board is determined that COAL shall continue to be plentiful, shall continue to keep our industrial power both dominant and progressive. You can depend upon COAL; its sources and supply are in our *own* hands—free from the fluctuations of foreign policies. Endless research by some of the world's greatest scientists and chemists working in the laboratories of the N.C.B. will ensure that coal will be increasingly profitable for its users.

DELIVERY—ON THE DOT —ON THE SPOT

The delivery of coal is today highly organised and completely reliable. Leading coal merchants have completely overhauled delivery and storage systems and are fully equipped to make sure that you get the right grade of coal when you want it and where you want it. And handling can be fully automatic. Furthermore, completely mechanised handling systems will transport coal from storage to furnace without any manual labour at all.

AND—WHEN YOU NEED IT— A NATION-WIDE FREE SERVICE

The vast resources of the National Coal Board are no further away than your telephone. At a flick of your finger, you can call upon one of the most comprehensive and efficient technical services in the world. No problem is too small or too big. You may want advice on coal quality, coal storage or coal-burning appliances or even on the siting of a new boilerhouse—whatever it is, a 'phone call or letter either to your coal supplier or to the Regional office of the National Coal Board will bring an authoritative answer to your problem.

FINANCE PLAN FOR INDUSTRY

No deposit, repayments spread over five years, low interest charges that can be set against Tax, full investment and other capital allowances, that can be claimed at once, these are the terms available to the manufacturer or businessman who wants to install modern coal-burning equipment without touching his capital resources.

Make use of the National Coal Board Industrial Finance Plan. The loans are made by Forward Trust Limited, who are members of the Midland Bank Group. A 'phone call or a letter to the Regional office of the National Coal Board will bring you full details.

SOLID FUEL—more heat at less cost—and it's British

PROGRESSIVE INDUSTRY IS GOING FORWARD ON COAL

ISSUED BY THE NATIONAL COAL BOARD

Abstracts

GROUP C — MASS TRANSFER (contd.)

Phase and Area Contributions to Mass Transfer Kinetics

This paper presents a relationship which has been developed to describe quantitatively the factors affecting packed column performance. This relationship is based on the Colburn equation and is proposed within the limits of a constant flow régime in the liquid phase. 25 refs.

A. J. TELLER, *A.I.Ch.E.J.*, 1961, **7** (1), 129-33.

Diffusion Rates in Porous Catalysts

The rates of diffusion of He, N_2 and CO_2 through cylindrical alumina pellets, $\frac{1}{4}$ in. dia. and $\frac{1}{4}$ in. long, were measured at atmospheric pressure and room temperature.

Knudsen type of diffusion appeared to be the controlling transport process and CO_2 diffused more rapidly than expected. 8 refs.

J. P. HENRY *et al.*, *A.I.Ch.E.J.*, 1961, **7** (1), 11-12.

The Graphical Representation of the Fractional Distillation of Ternary Mixtures

The paper describes graphical methods, based on the lever rule of mixing, with which the course of fractional distillation of the following ternary mixtures may be studied:

(a) The ideal kind and where the constant relative volatilities or binary temperature composition diagrams are known.

(b) The non-ideal kind for which certain equilibrium diagrams and/or isotherms are available.

K. L. BUTCHER, *Trans. Inst. Ch. E.*, 1961, **39** (1), 33.

Mass Transfer from Fluid and Solid Spheres at Low Reynolds Numbers*

Predicted continuous-phase mass-transfer coefficients for fluid and solid spheres in the Stokes region of flow are correlated as Sherwood numbers plotted against Peclet numbers. These correlations permit a study of the effect of internal circulation on the rate of mass transfer from fluid spheres. At a Peclet number of 10^4, the theory predicts a threefold increase in transfer due to the circulation movements within a gas bubble. At a Peclet number below 10^{-2}, the difference between a circulating and non-circulating (or solid) sphere is indiscernible.

The analysis presented in this paper for fluid spheres is based on a study by FRIEDLANDER of mass transfer around solid spheres. A more elaborate concentration profile through the boundary layer has been used in the present investigation and the result reported for solid spheres differs about 8 per cent from that given by FRIEDLANDER.

The more interesting details of the mathematical treatment and the machine computation of the resulting differential equations are included. 11 refs.

C. W. BOWMAN, D. M. WARD, A. I. JOHNSON and O. TRASS, *Can. J. Ch. E.*, 1961, **39** (1), 9-13.

The Fractionation of Gaseous Mixtures by Adsorption

Applied to the production of over-oxygenated air at ordinary temperatures.

Adsorption, traditionally reserved for gas purification problems, may become an autonomous and competitive process for the fractionation of gaseous mixtures of all compositions. This may be done by keeping near the region of "minimum work" conditions.

The following two rules must be observed: (a) isothermal use of an adsorption range of constant coefficient; (b) expansion following the admission, at higher pressure, of the initial mixture. The application of this method, known as "isothermal fractionation", will produce air containing up to 95 per cent oxygen at room temperature.

P. G. DE MONTGAREUIL and D. DOMINE, *Génie Chim.*, 1961, **85** S(2), 37.

Correlation and Prediction of Binary Vapour-liquid Equilibria

A new method of correlating and predicting binary vapour-liquid equilibria has been developed by analysing the changes in internal energy that occur during vaporization. A comparison of predicted and experimental vapour compositions gave an overall average deviation of about 1.7 mole per cent. Better agreement was obtained with hydrocarbon systems than with systems containing ketones. 20 refs.

R. GILMONT *et al.*, *Ind. Eng. Chem.*, 1961, **53** (3), 223-8.

* Author's abstract.

Mass Transfer Between Liquid Phases

Mass transfer coefficients for acetic acid in the two-phase system, methyl isobutyl ketone-water, have been determined as a function of concentration, in a circulating reactor, by means of a radio-active tracer technique. The results suggest that the mass transfer model needs re-examination. 19 refs.

C. A. EDWARDS and D. M. HIMMELBLAU, *Ind. Eng. Chem.*, 1961, **53** (3), 229-34.

Hold-up in Liquid-liquid Extraction Columns*

A theoretical study of the countercurrent flow of a dispersed phase in a continuous phase resulted in the following equation relating hold-up X to the flow rates of the two phases.

$$A\left(\frac{U_C}{U_D}\right)^{2-n}\left(\frac{X}{1-X}\right)^3 + B = \frac{X^3}{U_D{}^{2-n}}$$

For packed towers this equation has been used in the following form:

$$\frac{X^3}{U_D{}^{1\cdot5}} = A'\,\frac{U_C{}^r}{U_D{}^{1\cdot5}}\left(\frac{X}{1-X}\right)^3 + B'$$

Values of A', B' and r for three liquid pairs, and two packing types are reported, using new hold-up data determined in this research.

Graphical correlations are shown and values of r are reported for some of the data of GAYLER and PRATT.

For spray towers the equation suggested a correlation of $\frac{X^3}{U_D{}^{1\cdot8}}$ against the group $\frac{U_C{}^{0\cdot2}}{U_D{}^{1\cdot8}}\left(\frac{X}{1-X}\right)^3$. This has been tested using data previously published by one of the authors. 13 refs.

A. I. JOHNSON and E. A. L. LAVERGNE, *Can. J. Ch. E.*, 1961, **39** (1), 37-41.

Mixing and Contacting in Gas-solid Fluidized Beds

The author applies the two-phase model of a gas-solid fluidized bed to steady-state and transient gas mixing tests. Expressions are derived for gas back-mixing and for the standard deviation in gas residence time distribution, and it is shown that the gas eddy diffusivity of the dense phase and the rate of mass transfer between the two phases may be determined by suitable mixing tests. 12 refs.

J. J. VAN DEEMTER, *Ch. E. Sci.*, 1961, **13** (3), 143-54.

Graphical-numerical Determination of Variable Diffusion Coefficient in Solids

The paper presents a simple method for graphical analysis of concentration gradients in solids to determine the diffusion coefficient as a function of concentration. Problems encountered in extrapolation of data are considered, and it is shown that, if relative values of diffusion coefficient are the controlling factors, exacting extrapolation is not very necessary.

Two extrapolations are applied to given functional model; the results of one are greater and those of the other are less than the results predicted by the model.

R. S. HALL, *Can. J. Ch. E.*, 1960, **5**, 154.

Chemical Reaction Processes in Two-phase Systems: Theory and Experimental Results for Slow Chemical Reactions in Batch, Column and Continuous Stirred Tank Reactor Operations*

A theory of design of chemical reactors is developed for two-phase fluid systems where the rates of chemical reaction are low relative to the rates of mass transfer. Equations are presented for batch, column and continuous stirred tank operations. Experimental data on the continuous hydrolysis of acetic anhydride in a benzene-water system operating countercurrently in a pulsed-flow sieve plate column and in a packed column are analysed in terms of the theory. 6 refs.

P. TRAMBOUZE *et al.*, *A.I.Ch.E.J.*, 1961, **7** (1), 138-42.

Mass Transfer from Single Solid Spheres by Free Convection*

Rates of mass transfer by free convection have been measured for spheres of three organic acids dissolving in three solvents: water, n-butanol and benzene. The results fell into two groups, one in which flow is completely laminar and one in which turbulence had set in in the boundary layer. Turbulence appears to set in at $N'_{Ra\ crit} \sim 6 \times 10^8$. 15 refs.

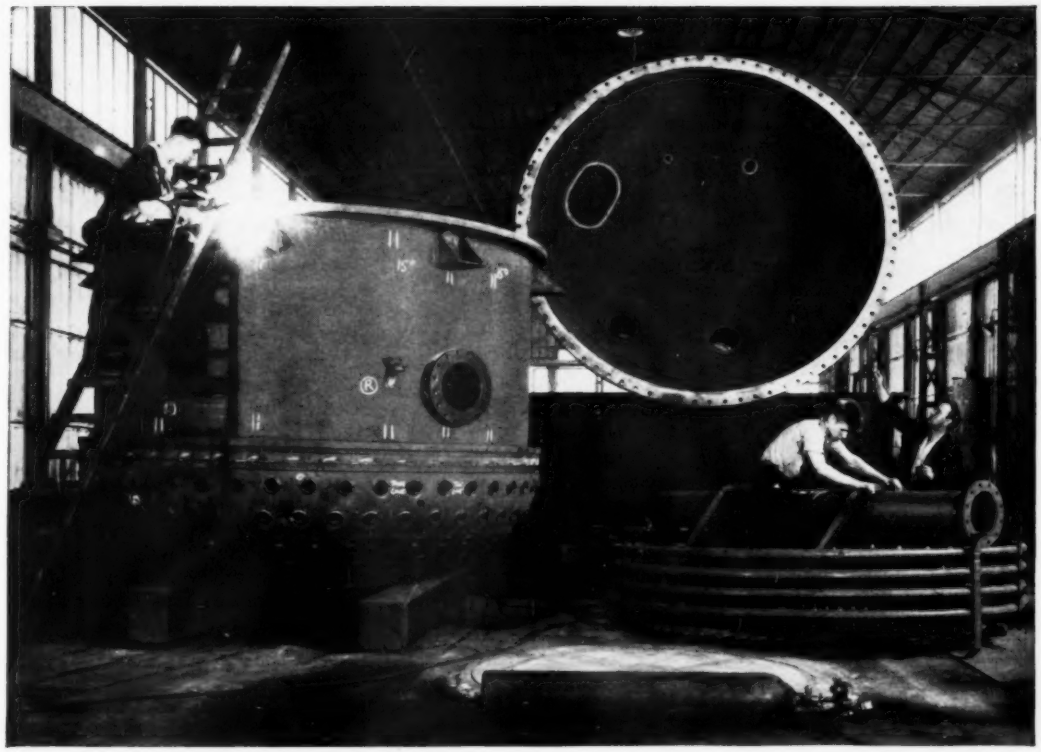
F. H. GARNER and J. M. HOFFMAN, *A.I.Ch.E.J.*, 1961, **7** (1), 148-52.

Further Studies of Fluid Flow and Mass Transfer in Trickle Beds

Residence time studies are reported for water trickling down a 4-in. column packed with porous and non-porous spheres. The response of the column to pulse and step additions of different tracers in the water was determined. Significant radial variations in the distribution of residence times and flow rate were observed.

W. E. SCHIESSER and L. LAPIDUS, *A.I.Ch.E.J.*, 1961, **7** (1), 163-71.

Brit. Chem. Eng. Abstracts: **FOLIO No. 7**



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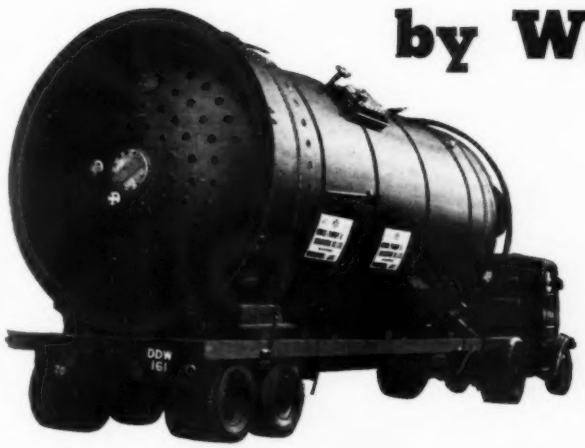

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Above: Work in progress on the construction of two mild steel carburettors.

Left: One of two mild steel carburettors.

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Abstracts

GROUP D — PHYSICAL SEPARATIONS

Scale-up of Dust-removal Plant

The scale-up of such plant is demonstrated in a case history of a problem concerning the removal of carbon black from a fully saturated gas.

C. A. Bainbridge, *Chem. Proc. Eng.*, 1961, **42** (3), 115-16.

Scale-up for Drying and Filtration Plant

This short article describes how scale-up is effected, from pilot plant to full-scale plant, by a company that specializes in the construction of such equipment.

Chem. Proc. Eng., 1961, **42** (3), 113-14.

GROUP E — PROCESSING

Sodium Reactor Operating Experience

The sodium reactor experiment was launched to obtain information on the possibility of full-scale sodium-graphite reactor plants becoming competitive with conventional power plants. The paper describes the sodium-graphite reactor, its operation and problems that arise therefrom. The conclusion appears to be that power generation by means of such a reactor is feasible. The superheated steam produced is of high quality. Operating experience since 1957 has produced information equivalent to 20 years with a production-type power reactor.

R. E. Durand, *C.E.P.*, 1961, **57** (3), 54-9.

The Hydrate Process

This paper presents engineering development details on the hydrate process. This is a chemical approach to water desalination and is claimed to be economically competitive with present physical processes.

W. G. Knox *et al.*, *C.E.P.*, 1961 **57** (2), 66-71.

Opencut Mining Equipment in Australia

The author presents a survey on 16 opencut mines considered representative of current Australian practice. 9 refs.

R. W. L. King, *Min. & Chem. Eng. Rev. (Aust.)*, 1961, **53** (4), 32.

Electrodialysis—Equipment and Membranes

Electrodialysis has recently been considered in connection with saline water conversion. This paper surveys present designs and a variety of methods for preventing scale. Further improvements in membranes, equipment, methods of scale prevention, etc., are needed before the full potential of this process may be realized. 10 refs.

H. J. Cohan, *C.E.P.*, 1961, **57** (2), 72-6.

Checking and Controlling Vacuum Processes

The drying of caprolactam chips, vacuum drying of oil-filled cables and freeze drying of foods have helped to show how the course of the process in the high vacuum range (1 to 10^{-3} mm Hg) can be checked and controlled by measurement of the rise in pressure. This method can also be modified for ultra high vacuum. 16 refs.

M. Beyer *et al.*, *Chemie Ing. Tech.*, 1961, **33** (3), 185-90.

Constructional Form of Two Vacuum Columns of Large Dimensions with Air-cooled Condensers

The extension of the styrene plant of Chemische Werke Hüls AG has two large-diameter columns with air-cooled condensers characterized by several special constructional features. The construction of these columns, the use of air as the cooling medium and the arrangement of the condensers at the head of the columns disclose interesting possibilities for the design of distillation plants.

J. Dodt, *Chemie Ing. Tech.*, 1961, **33** (3), 205-9.

The Thermal Treatment of Materials using Electron Beams

When an electron beam strikes a substance of sufficient density, about 90 per cent of the energy carried by the beam is absorbed as heat in the substance. Since electron beams can also be accelerated in electric fields, as carriers of negative electricity, additional energy can be imparted to them so that very high energy densities can be obtained. These can be used for boring, cutting and welding metals and high fusion-point substances. The author describes the present state of development in this field. 9 refs.

K. H. Steigerwald, *Chemie Ing Tech.*, 1961, **33** (3), 191-4.

The Production and Utilization of Butadiene

Commercial processes for producing butadiene include the Aldol process, dehydrochlorination of dichlorobutane, hydrolysis of cyclohexane, the Reppe process, dehydration of alcohols, dehydrogenation of butane and butene, and cracking processes. Tabulated details are given of the distribution of these processes showing that the one-step Houdry process is gaining ground.

Extraction processes for purifying crude butadiene include cuprous ammonium acetate process and furfural process. Butadiene is utilized in the manufacture of synthetic rubbers and adiponitrile for nylon.

A. A. Appleton, *J. Inst. Pet.*, 1960, **46**, 367-73.

Preparation of Pure Barium and Strontium Carbonates

The paper presents a method of preparing a pure barium and strontium carbonate required in either: (1) In gram quantities of high purity for the preparation of standards for flame photometry and spectral analysis. (2) In kilogram amounts of somewhat reduced purity for the production of special experimental ceramic masses. The method of separation described is based on different solubilities of chlorides of alkaline earths in excess of HCl, of nitrates in excess of HNO_3 and on the insolubility of barium chromate in neutral medium, respectively.

L. Plocek, *Chem. Prum.*, 1961, **11** (3), 129-31.

Heat Exchange from Gases at High Temperature in Combined Co- and Counter-current Processes

When it is necessary to heat a gas in a heat exchanger to a temperature which can only be reached by counter-current operation and, at the same time, to operate at a temperature level which requires co-current operation, the problem of design and construction of a combined co- and counter-current heat exchanger arises.

Calculations involve the solution of a differential equation system, which can only be solved in closed form if heat exchange by radiation is neglected. The calculations to evaluate the numerical solution in the general case are so complex that an electronic computer is needed. This paper discusses the two types of solution and a suitable form for the combined heat exchanger.

K. Schack, *Chemie Ing. Tech.*, 1961, **33** (3), 163-6.

Isolation of p-Xylene from Black-coal Tar

A description of a process for isolating p-xylene from black-coal tar. Experiments were performed on a pilot plant to find optimum operating conditions. For the production of p-xylene the xylene fraction used was that normally produced at the Urx Works (Czechoslovakia).

The results of the experiments show that p-xylene can be obtained from black-coal tar, of a quality rendering it suitable for further processing. It appears to be economic to carry out the separation of p-xylene along with the utilization of other processes, especially the oxidation of o-xylene to phthalic acid.

Experimental work is being conducted at the pilot stage on p-xylene production from xylene fractions derived from other sources. 1 flow diagram, 12 refs.

M. Janik, *Chem. Prum.*, 1961, **11** (3), 112-17.

Hydrazine Production by Nuclear Reaction

A joint U.S.A.F.-industry team investigates the possibility of the direct, in-reactor production of hydrazine from liquid NH_3. In this fissio-chemical process a nuclear reactor is designed to directly convert the energy evolved by the fission process into the transformation of chemical bonds. This paper outlines the general fissio-chemical concept, its particular application to the production of hydrazine, and presents details of the initial experimental investigations. 11 refs.

L. P. Fritsch Jr. *et al.*, *C.E.P.*, 1961, **57** (3), 37-41.

Auto-oxidation of Chlorotrifluoro Ethylene

An account of an investigation into the mechanism and kinetics of oxygen reaction with chlorotrifluoro ethylene, the bulk and the suspension polymerization of which are adversely affected by the presence of atmospheric oxygen.

It was found that the predominant products of oxidation are a peroxide $(C_2Cl\,F_3O_2)_n$, chlorodifluoro acetylfluoride. The oxidation has a relatively long inhibition period which is indirectly proportional to the initial concentrations of monomer and oxygen. After the elapse of the inhibition period, the reaction takes an autocatalytic course, its rate being directly proportional to the square root of the concentration of peroxide up to about 30 per cent conversion of oxygen. This fact corresponds to a monomolecular degradation of polychlorotrifluoro ethylene peroxide.

D. Ambros, *Chem. Prum.*, 1961, **11** (2), 60-5.

Brit. Chem. Eng. Abstracts: **FOLIO No. 8**

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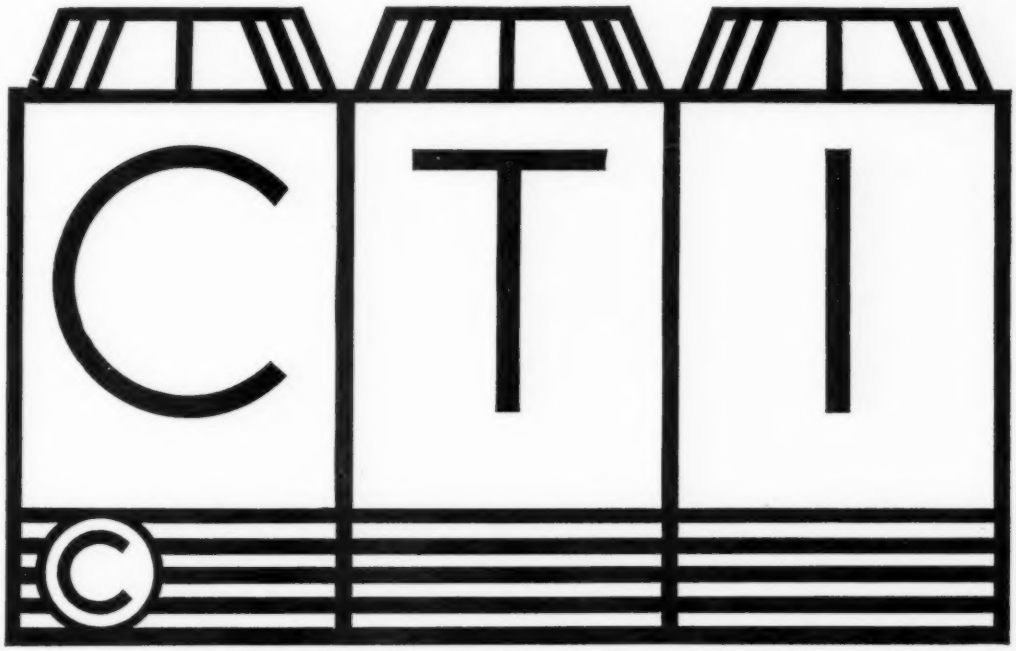

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Abstracts

GROUP E — PROCESSING (contd.)

Organic Moderated Reactor

This paper concerns an investigation into the technical and economic feasibility of a thermal power reactor which uses a liquid hydrocarbon as the coolant and moderator. Operating experience has shown that (1) the hydrocarbon reactor coolant is compatible with standard materials of construction; (2) maintenance and modifications can be performed without serious radiation hazards, with conventional tools and without highly skilled craftsmen.

Additional information, necessary for the design of full-scale reactors, is being obtained.

N. J. Swanson, *C.E.P.*, 1961, **57** (3), 60-3.

The Development of the Alum-amine Process for the Recovery of Alumina from Shale

Based on a review of the extensive published literature on the recovery of alumina from clays and shale, enough experimental work was done on a bench scale to establish a flow sheet whereby these materials might be treated for the recovery of cell-grade alumina. The significant step in the processing is the recovery of potassium alum and its purification by either recrystallisation or liquid-liquid extraction.

G. Thomas and T. R. Ingraham, *Can. J. Ch. E.*, 1960, **6**, 220.

The Formation and Conditions for Formation of Natural Synthetic Diamonds and other Natural and Synthetic High-pressure/High-temperature phases

The author discusses the genesis and paragenesis of natural diamonds and the present state of the graphite-diamond transformation diagram. He also discusses present synthesis and the conditions which are essential to diamond formation and synthetic production. Data are presented on the construction of modern high-temperature/high-pressure autoclaves and on the reaction kinetics of nucleus formation and growth of synthetic diamonds.

Scientific and industrial fields in which the new high-temperature/high-pressure technology can be applied are outlined. 23 refs.

A. Neuhaus, *Chemie Ing. Tech.*, 1961, **33** (3), 220-4.

Hydrocarbon Synthesis

The authors present a survey of the synthesis process, developed by Kölbel and Engelhardt, based on the catalytic reaction to produce paraffinic and olefinic hydrocarbons, as well as a wide spectrum of oxygenated compounds, from carbon monoxide and water vapour. Catalysts are elements of group VIII of the Periodic Table (Fe, Co, Ni, etc.).

The Kölbel-Engelhardt synthesis has been tested in a fixed-bed reactor and in a liquid-phase reactor with catalyst slurry. Best results have been obtained in a gas-bubble column reactor which is described.

H. Kolbel and H. Hammer, *Chem. Proc. Eng.*, 1961, **42** (3), 105-11.

Preparation of Sodium Pyrosulphite from Waste Gas in H_2SO_4 Production

A process is described for utilizing the SO_2, in the waste gases, to produce sodium pyrosulphite, used in agriculture to preserve ensilaged fodder. SO_2 is absorbed in a circulating solution of sodium carbonate containing some sodium pyrosulphite. During circulation, Na_2CO_3 is added to keep the proportion of acidic and alkaline components (S_2O_4 : NaOH) at about 0.85 : 1. Efficient and rapid removal of precipitated sodium pyrosulphite is effected by a hydrocyclone of suitable dimensions.

The first full-scale industrial unit was designed on the basis of laboratory investigation into the physical and chemical conditions of pyrosulphite formation and on experience gained in a pilot plant.

R. Klimecek and J. Bettelheim, *Chemicky prumysl*, 1960, **10** (4), 190-2.

Chemical Reactor Design

In the design of a homogeneous reactor a decision must first be made on the type of reactor to be used, and the optimum operating conditions must then be found. This paper shows how a high-speed computer may be used in such a design, especially in determining optimum conditions. 13 refs.

G. T. Westbrook and R. Aris, *Ind. Eng. Chem.*, 1961, **53** (3), 181-6.

Pelletizing Magnetic Taconite Concentrates

Mixtures of peat and alkali function effectively as a binder for pelletizing magnetic taconite concentrate. Dried taconite pellets, with satisfactory crushing strength, were obtained by mixing 7.5 lb of peat and 1.0 lb of NaOH (or 2.5 lb Na_2CO_3) per ton of concentrate. It appears that the crude humic acid content of the peat is largely responsible for the binder action. 5 refs.

E. L. Piret *et al.*, *Ind. Eng. Chem.*, 1961, **53** (3), 215-16.

Direct Hydration of Olefins with Cation Exchange Resins

This study shows that at low temperature (150-250°F) and low pressure (150-425 psig), 27-32 mole per cent of the isobutylene content of C_4 refinery streams and 10 mole per cent of the isoamylene content of a C_5 refinery stream were selectively converted to tert-butyl and tert-amyl alcohols, respectively, by direct hydration using a cation exchange resin catalyst. Catalyst activity was maintained for long periods. This method, coupled with dehydration, affords an economical means of preparing pure alcohols or pure iso-olefins from refinery streams. 5 refs.

R. C. Odioso *et al.*, *Ind. Eng. Chem.*, 1961, **53** (3), 209-11.

The Catalytic Treatment of Nitric Acid Plant Tail Gas

A description of catalytic treatment of nitric acid plant tail gas containing O_2, NO, NO_2 and H_2O in N_2. The oxides and O_2 were reduced to a few ppm, with one or more platinum group metals as catalysts, at space velocities over 60,000 scf/hr/cu ft catalyst, using any reducing gas in slight excess over the total oxygen. When O_2 content is over 4.2 per cent, two catalytic stages with inter-cooling are needed to obviate high temperatures on the catalyst and vessel.

A selective catalytic process for removing NO and NO_2 by NH_3, in slight excess over these oxides, is also described. 16 refs.

H. C. Andersen *et al.*, *Ind. Eng. Chem.*, 1961, **53** (3), 199-204.

A Method of Measuring the Surface Area of Granular Material

In this method the material is coated with an adhesive and a single layer of small metal particles. The change in weight gives a measure of the external area. The method is applicable to particles with a minimum external area of 0.1 in.^{2} and is intended for use in research where the surface area of objects has a bearing on the investigation; e.g., the drying of grains and foodstuffs, the comminution of ores and chemicals and the hydraulic and pneumatic transport of materials.

The root mean square error of this method is about 1 per cent. 3 refs.

C. P. Hedlin and S. H. Collins, *Can. J. Ch. E.*, 1961, **39** (1), 49-51.

Steam-oxygen Gasification of Fine Sizes of Coal in a Fluidized Bed at Elevated Pressure

Part I: Reaction of Carbon with Hydrogen. Part II: Reaction of Carbon with Steam. Part III: Relation of Integral to Differential Rates; Effect of Carbon Level on Gasification Rate, and Role of the Shift Reaction.

Kinetic data are presented from operations of a fluid-bed gasifier, 26.5 in. ID, operated at a bed-depth of 25 ft. Anthracite fines were gasified with steam and oxygen at pressures up to 245 lb/in^{2}g and temperatures up to 1676°F. Up to 650,000 scf per day of H_2, CO and CH_4 were produced.

Part I deals with the formation of CH_4 in fluid-bed gasification. This is generally determined by approach to a "quasi-equilibrium" between char, CH_4 and H_2. Char has a free energy higher than graphite and the excess free energy is related to thermal data obtained on carbons of various surface areas.

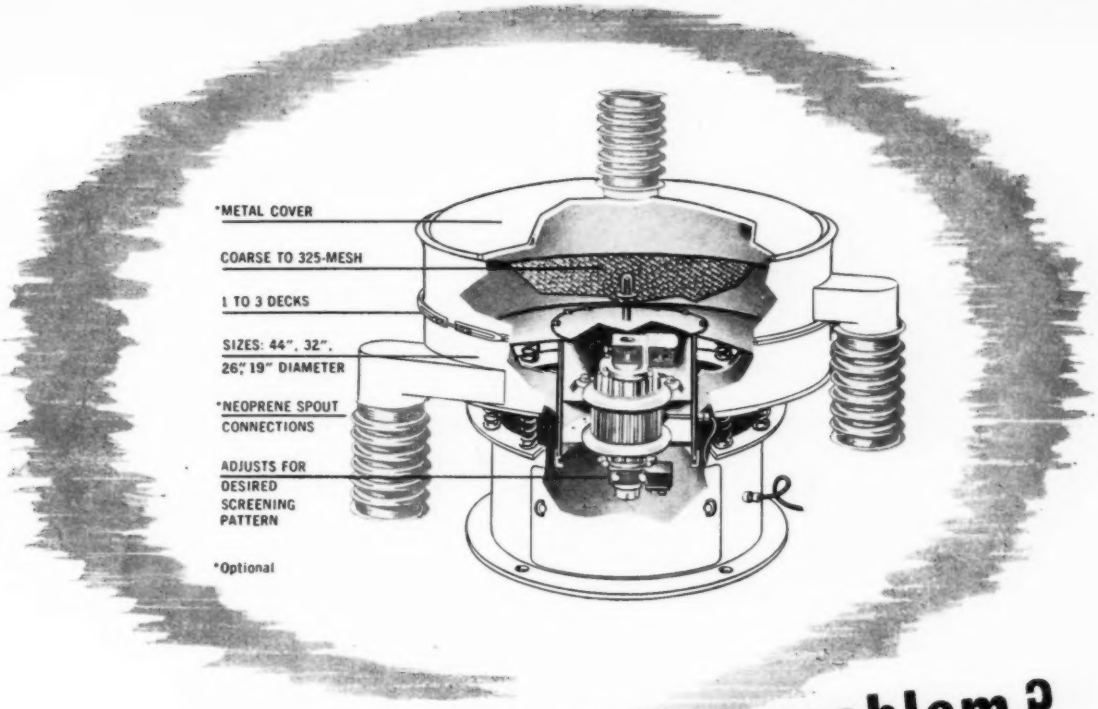
Part II treats the steam carbon reaction. An empirical correlation which is applicable to anthracite and chars of bituminous coals is given for integral rates of this reaction in the fluid bed. Fluid-bed hydrodynamics have an important effect on the kinetics of this reaction. Top-to-bottom circulation of solids results in periodic reactivation of carbon near the bed-bottom, where the partial pressure of steam is high and that of H_2 is low. Carbon activity is high throughout the bed. In a fixed-bed gasifier, operating above 1600°F, carbon activity is high near the steam inlet and low at the gas outlet. This gradient in carbon activity may cause a reduction in methane yield.

Part III discusses the problem of relating the empirical correlation for integral rates of the steam-carbon reaction with the appropriate differential rates.

An empirical correlation is presented for the water-gas shift reaction, which appears to be relatively slow in the available fluid-bed gasification experience.

A. M. Squires, *Trans. Inst. Ch. E.*, **39** (1), 3-27.

Brit. Chem. Eng. Abstracts: **FOLIO No. 9**



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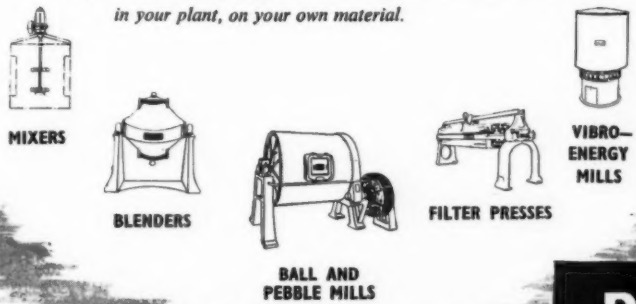

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Abstracts

GROUP F — PROCESS CONTROL

Two New Instruments for Measuring the Air Content of Oil

The paper describes two new instruments for measuring the air content of mineral oil. A sealed sample of oil is fed to an evacuated de-aeration chamber and the rise in pressure, resulting from de-aeration, is measured. Special sample bottles for sampling oil under pressure or vacuum are described. One instrument features a vibrating stirrer and is considered to be more suitable for general use. The accuracy of both has been found to be within ±3 per cent.

A. T. J. Hayward, *J. Inst. Pet.*, 1961, **47** (447), 99-106.

GROUP G — MISCELLANEOUS

Chart for Wall Thickness

A chart has been prepared to facilitate the calculation of vessel wall thickness in accordance with the A.S.M.E. code of 1959. The revisions in this new code are outlined and include the corrosion allowance, vessel supports, manholes and welding quality.

D. C. Enos, *Pet. Eng.*, 1960, **32** (6), C26.

Design of Steam Tracing Systems for Protection Against Freezing

The paper describes a satisfactory method of designing insulated steam tracing systems which offers an advantage where heat-sensitive materials are to be protected against freezing. The method may be applied to tracers containing heating media other than steam, and it provides a satisfactory alternative to bonding the tracer to the pipe and transferring heat by conduction, if moderate overheating of a process material is not a consideration.

W. S. Cotton, *Can. J. Ch. E.*, 1960, **6**, 214.

The Effect of Mixer Design on the Efficiency of a Pump-mix Mixer-settler

The mixing efficiency of simple and pitched paddles, marine propellers, centrifugal and disc impellers (3 to 5 in. dia.) was determined by a heat transfer method in a single stage of a large pump-mix mixer-settler, where kerosene was the organic phase and water the aqueous phase.

A heat conductance UA was calculated from flow parameters and the efficiency, and was correlated against impeller design and speed variables. For centrifugal and disc impellers UA was $\propto n^{1.2}\ L^3\ b^{0.3}$; for the paddles UA was $\propto n^{1.67}\ L^{2.5}\ b^{0.42}$. At normal operating speeds, the efficiency was not altered by the controlled variation of the internal recirculation of mixed phases through a centrifugal impeller. 9 refs.

A. T. Davis and T. J. Colven, *A.I.Ch.E.J.*, 1961, **7** (1), 72-7.

Corrosion—Generated Hydrogen Explodes in Phosphoric Acid Tank

An investigation of an explosive reaction in a stainless-steel tank storing 75 per cent H_3PO_4 showed H_2 probably ignited by electrical level control. Hydrogen gas is produced rapidly when H_3PO_4 contaminated with chloride corrodes type 304 stainless steel.

J. B. Lowe, *Corrosion*, 1961, **17** (3), 30-2.

Small Distillation Column Efficiency

A relation has been developed for small distillation columns between the properties of the system and the plate efficiency. The empirical correlation:

$$E = 0.0691 \left(\frac{\sigma}{\mu_L\ V_g}\right)^{0.64} \left(\frac{\mu_L}{\rho_L\ D_L}\right)^{0.19} \left(\alpha\right)^{0.056}$$

predicts efficiencies within an absolute average deviation of 3.5 efficiency units.

P. Chaiyavech and M. Van Winkle, *Ind. Eng. Chem.*, 1961, **53** (3), 187-90.

Selection and Evaluation of Contact Catalysts

The paper describes a systematic approach to the selection and evaluation of contact catalysts, with reference to available techniques and procedures given in the literature. 82 refs.

E. H. Lee, *Ind. Eng. Chem.*, 1961, **53** (3), 205-8.

This Ammonia Unit Exploded

The paper reviews a series of events leading to the disastrous explosion of the ammonia synthesis process at the Kyowa Hakko Kogyo Co.

Yoshio Sakai, *Pet. Ref.*, 1961, **1**, 178

Single Tower, Low Pressure Absorption Plant for Production of Nitric Acid from Nitrous Gases

(*Brit. Chem. Eng. Abstracts* Folio No. 4 April issue, 272.)

The reference, which was omitted, is:

L. H. Hesky, *Chemie. Ing. Tech.*, 1961, **33**, 27.

A New Corrosion-resistant Concrete: Its Use for the Construction of Pipes and Sewers

The "Ocrate" process consists in treating previously dried concrete with gaseous silicon tetrafluoride. This treatment confers on concrete an increased resistance to the corrosion of salt and acids and permits its use in conduits for industrial waste waters and town sewage.

G. Roederer, *Chimie et Ind.*, 1960, **84** (6), 912.

Cut Evaporation Losses from Storage Tanks

A process is described for cutting evaporation losses from storage tanks by circulating the heated air and vapours through an external heat exchanger and returning them to the top of the vapour space.

Circulation is automatic.

C. A. Basore, *Oil Gas J.*, 1960, **58** (32), 99-100.

Design Factors and Comparative Costs for Low-temperature Piping Materials

A description is presented of materials best suited for use in various low-temperature ranges. Mention is made of some advantages of non-ferrous and non-metallic materials and of the safety problems which may arise from their use.

H. M. Howarth, *Pet. Eng.*, 1960, **32** (7), C33.

Extractive Reaction: Batch- and Continuous-flow Chemical-reaction Systems, Concentrated Case

The theory of extractive reaction is extended to concentrated solutions where the distribution coefficients are no longer constant and where important changes in phase volumes may occur. The methods developed are applicable to simple or complex reactions of any order. Two- and one-solvent systems are treated, and convenient graphical methods are developed and illustrated with numerical examples.

P. J. Trambouze and Edgar L. Piret, *A.I.Ch.E.J.*, 1960, **6** (4), 574.

A Study on the Thermodynamics of Methanol Decomposition and on the Catalyst of This Reaction: Part 1

The thermodynamics of methanol decomposition in the gas phase was examined; in addition to carbon monoxide and hydrogen (the main reaction products), the presence of formaldehyde and methyl formate was also considered. Formulæ were developed for the dependence on the temperature of several thermodynamic values characterizing the system, including: enthalpy, the logarithm of the equilibrium constant, and the thermodynamic yield of the reaction examined for the pressure $p = 1$ atm. 13 refs.

A. Frackiewicz, *Przem. Chem.*, 1960, **39** (12), 752-6.

Tubular Reactor Sensitivity

Reactor sensitivity is defined as the ratio of the standard deviation of an output to the standard deviation of an input. In this paper, the general theory is developed mathematically and two examples are presented to illustrate the method. 7 refs.

J. Coste *et al.*, *A.I.Ch.E.J.*, 1961, **7** (1), 124-8.

Design of Experiments on the Kinetics of the Water-gas Shift Reaction

Experiments have been carried out on the continuous catalytic water-gas shift reaction $CO + H_2O \rightarrow CO_2 + H_2$, and the principles of statistical design used to elucidate the reaction mechanism. Instantaneous reaction rates were determined for 16 combinations of the 5 variables: partial pressures of CO, H_2O, CO_2 and H_2, and temperature. N_2 was used to bring total pressure up to 1 atm.

The results indicate that the Temkin mechanism cannot represent the data within experimental accuracy, and an alternative mechanism is presented. 11 refs.

H. M. Hulbert and C. D. Srini Vasan, *A.I.Ch.E.J.*, 1961, **7** (1), 143-7.

Size Distribution of Droplets from Centrifuge Spray Nozzles

The paper discusses methods of expressing, measuring and correlating drop-size distribution data for centrifugal spray nozzles. A method for collecting spray droplets in liquid nitrogen, which is rapid and efficient for most sprayed liquids which freeze at −20°C, is described. Comprehensive correlations for drop-size distributions, based on 114 runs performed with this liquid nitrogen method, are reported. 16 refs.

P. A. Nelson and W. F. Stevens, *A.I.Ch.E.J.*, 1961, **7** (1), 80-6.

Brit. Chem. Eng. Abstracts: **FOLIO No. 10**

Important application for Vickers Strip-wound High Pressure Vessels

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EVAPORATION FROM PONDS AND THICKENERS (Contd)

by D. S. DAVIS

(Head, Department of Paper and Pulp Technology, University of Alabama)

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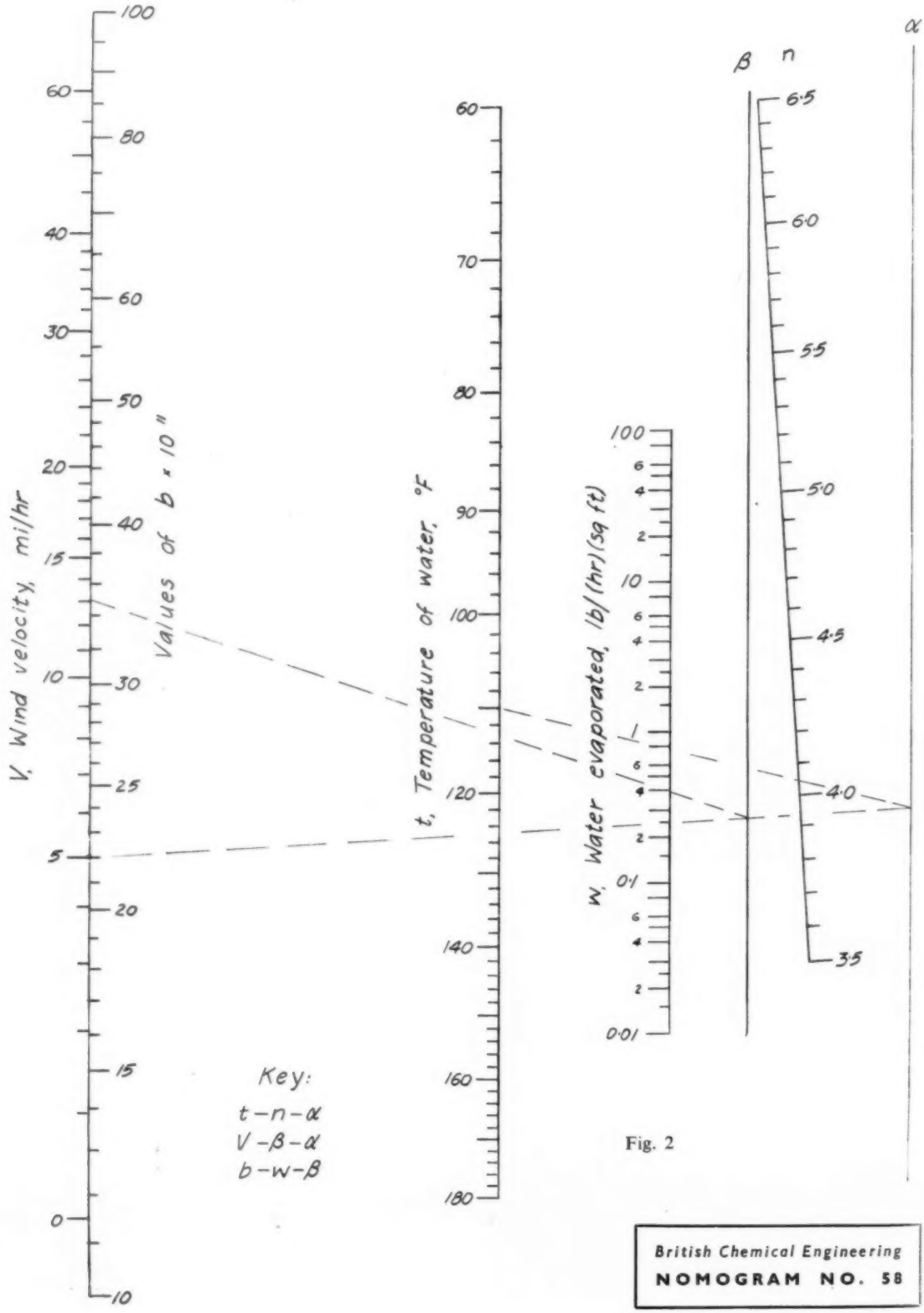

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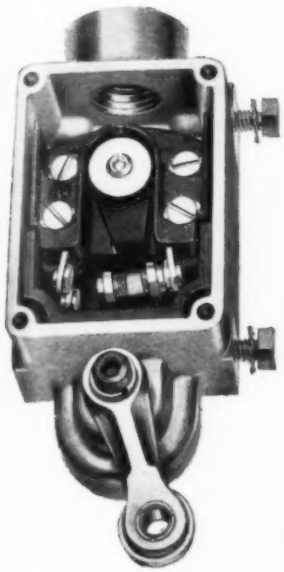

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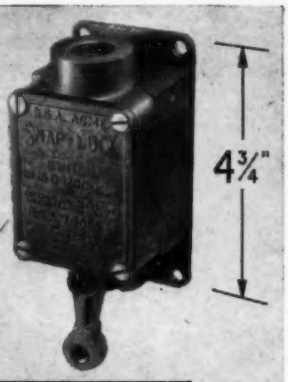

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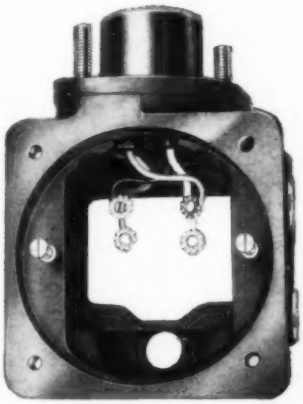

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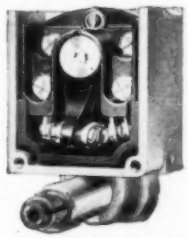

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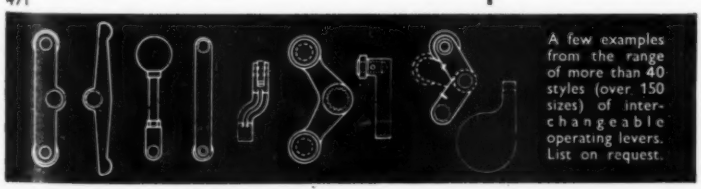

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AMERICAN LETTER

Compact Reduction Processes for Iron and Steel

THE application of chemical engineering principles in the iron and steel industry has helped to accomplish several major developments. For example, viewing the blast furnace as a reactor instead of a traditional metallurgical tool has led to new smelting techniques involving the use of oil and oxygen. By such means, huge increases in output and several other operating benefits have been attained without corresponding additions to capital investment or the construction of still larger furnaces.

Surprisingly enough, much development work has also been undertaken in the U.S.A. and other countries towards entirely eliminating the blast furnace and its costly entourage of coke ovens, stoves and ancillary equipment. This is not primarily due to a search for still greater efficiency, but mainly arises from a need for compact smelting plants in strategic locations where a conventional iron and steel complex would be ruled out because of size and cost. Just as the tilting-arc furnace has enabled numerous small steel producers to become established near suitable markets and sources of scrap, so a compact iron-reduction process would enable advantage to be taken of raw material sources limited in quantity and quality. In addition, an optimum size of plant could be chosen, in accordance with local needs.

Processes Yielding Pig Iron or Steel

Commercial U.S. processes in this category include the Strategic-Udy, the Dwight-Lloyd-McWane (offered by the McDowell Co.) and the Orcarb process of the Swindell-Dressler Corporation.

The Strategic-Udy process employs a rotary kiln to pre-reduce a continuous feed of iron ore, carboniferous material and limestone prior to final smelting in an arc furnace of special design. This furnace is of the open-arc type and the off-gases are used to fire the rotary kiln. Typical production costs (excluding iron ore cost) are said to be about $22 per ton of metal produced, based on a 500 ton per day plant, which costs between 5 and 8 million dollars, according to the extent of site facilities and other needs. A feature of this process is the ability to use low-grade ores and complex, iron-containing materials. For example, an S.U. plant is to be installed in Anaconda, Montana, to produce steel from a 40-million-ton pile of copper slag. Other plants of this type are planned for Arizona, Venezuela and Canada.

In the D.L.M. process the charge is first pelletized by a McDowell pan machine and pre-reduced in a Dwight-Lloyd down-draught sinterer to about 70 per cent metallic iron, before final smelting to pig iron in a submerged-arc furnace. Production costs and capital investment per ton are similar to those for a Strategic-Udy plant, according to extensive tests made on a 10 ton per day pilot unit. The Orcarb process, which has also been widely tested on a pilot scale, uses a rotating retort to pelletize the charge of ore, flux and coking coal, prior to pre-reduction in a rotary kiln and subsequent smelting in an arc furnace.

Processes for Making Sponge Iron

In Sweden, sponge iron manufacture by direct reduction has been undertaken for many years via the Wiberg-Soderfors process, and similar installations are now planned for Japan. Although this process has not been adopted in the U.S.A., interest in producing commercial tonnages of sponge iron has grown appreciably in recent years and several interesting methods based on modern chemical engineering have been developed, some are in operation.

Perhaps the most firmly established process of this type is the one developed by Hojalata Lamina S.A. of Mexico and the Kellogg Co. of New York. Two HyL plants with a total capacity of 700 tons per day are now in operation in operation in Monterrey, Mexico, and further installations are under consideration in Canada and other countries. This is a batch process in which a charge of rich ore or sinter is reduced by hydrogen and carbon monoxide (produced from steam-reformed natural gas) at temperatures in the region of 2000°F. Hot sponge discharged from the batch reactors preheats the incoming natural gas, prior to being fed to arc furnaces for conversion to steel.

Two other direct-reduction methods of sponge iron manufacture are the R-N and the E.R.L. processes. The first was developed by the National Lead and Republic Steel companies and uses a rotary kiln equipped with burners and manifolds of ingenious design to reduce a mixture of iron ore and carboniferous material to sponge iron. The product is wet-ground and beneficiated to about 90 per cent iron before being briquetted for use as an electric furnace feed, and considerable tonnages have been made in a semi-commercial plant. The second process, jointly developed by Esso Research and Arthur D. Little Inc., is based on the reduction of low-to-medium grade ores by gas produced in a partial-oxidation plant, and a three-compartment, fluidized bed reactor is used, operating at about 1600°F and 1 to 4 atm. The sponge produced contains about 85 per cent iron.

Processes for Making Powdered Iron

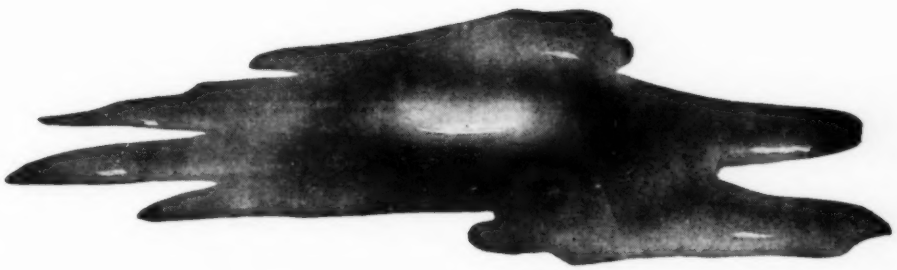
The H-iron process, which was jointly developed by the Bethlehem Steel Co. and Hydrocarbon Research Inc., produces iron powder for metallurgical and catalytic purposes by the reduction of high-grade ore with hot hydrogen in a three-stage fluidized reactor. The reaction temperature is about 1000°F, and although pressures up to about 650 psig are used, the process is operated continuously by employing ingenious "dense phase" solids transportation between stages, together with final passivation of the pyrophoric iron powder in a nitrogen atmosphere. A 50 ton per day plant at Conshohoken, Pa., produces high-quality, low-carbon iron for powder-metallurgy purposes, and a 110 ton per day plant has been built in Los Angeles to supply feed for electric furnace operations.

Another fluidized-bed method for producing powdered iron has been developed by the U.S. Steel Corporation and is known as the Nu-iron process. This uses a two-stage vertical reactor, which operates at about 1600°F and 20 psig, to yield a product containing up to 95 per cent pure iron. Also of interest is the Maderas process which is based on the batch reduction of iron ore in retorts, by steam-reformed natural gas at a temperature of nearly 2000°F and pressures of about 40 psig. A 100 ton per day semi-commercial plant has been built in Dallas, Texas.

In addition we may mention the Direct Steel method, which is under development by the Ontario Research Foundation. This aims to produce steel strip directly from high-grade oxide.

Because Vessels Sometimes leak...

...and People Sometimes spill...



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Book Reviews

Chemical Engineering Economics
by Chaplin Tyler and C. H. Winter, Jr.
McGraw-Hill Book Co., 4th Edition, 1959, 187 pp.

THIS book on the role of economics in industrial enterprises was originally published in 1926. Now it has been extensively revised and rewritten. It is based on the American chemical industry, and one of its uses is obviously as a text-book for their undergraduate courses in chemical engineering. Our courses, unfortunately, do not deal so thoroughly with these aspects. This book should be of considerable assistance in making good this omission.

The role of economics is analysed by considering first various methods of accounting, showing the differences necessary when the costing is applied to a "job" or "batch" or to a "process" or to cover a "period" when the process is a continuous one. It only briefly defines "standard costs", without much explanation of its use or potentialities, nor does it debate the pros and cons of "standard costs", which is a pity as this system of accounting has a fairly widespread use in this country. Another chapter deals with the financial analysis of a company's results, showing how return on investment can act as a barometer for a company's progress, and how it can be used for forward estimating. Examples are given to show how a new product requires a year or so to become established, then follows a period of very profitable activity, which slowly declines to a point where the production should be discontinued. No consideration, however, is given to the problem of how to allow in such an analysis for the fluctuations in the general level of trade during these periods, and how to allow for their effects on the assessment of the fortunes of an individual product. A number of cases are illustrated from American experience. It would be interesting to study how British experience simulates or differs from these American examples.

The tricky problem of how much research a company can afford to undertake and of the type of research is tackled well. The American average that $1 spent on research should lead to a possible investment of only $2 to $3 is rather surprising. Again facts from British experiences would be interesting.

Other chapters deal with process development, project engineering, project evaluation and manufacturing costs. These are well illustrated with examples, which will assist in tackling similar problems, even if the latter never come out with such clear answers as text-book examples always do.

This book discusses a number of important problems, especially those relating to such questions as "will it pay?", and the answers given should prove helpful with many problems present in all organisations. The reader of this book will realise the need for similar analyses related to the background of British industry, but until such a book appears, this one fulfils a need.

R.S.B.

The Aerodynamic Capture of Particles
by E. G. Richardson
Pergamon Press, 1960, 200 pp., 50s.

THE chemical engineer recognises increasingly that *particle mechanics*, the study of heat, mass and momentum transfer in systems containing particles, is a branch of two-phase flow. Next year's symposium by the Institution of Chemical Engineers on the *Interaction of Fluids and Particles* serves as a strong indication of its importance. The realisation that there is a unifying science behind the manifold operations which it covers is a relatively new feature.

Aerodynamic Capture of Particles, i.e., the collision of gas-borne particles either with each other or on larger particles, is a process in which the meteorologist had a prime interest. The particle mechanics of the system is, however, common to many operations of direct concern to the chemical engineer such as de-misting and de-dusting of effluent gases, particle behaviour in froth floatation, deposition of particulate matter from combustion gases on turbine blades, dust deposition on fibrous filters, deposition of radioactive fall-out on the ground and so on. Research work in these operations forms the subject of papers which were delivered at a symposium organised by the late PROFESSOR E. C. RICHARDSON of King's College, Newcastle upon Tyne. These papers, together with others on miscellaneous topics and the valuable discussion following their presentation, are contained in the book under review.

Some fundamentals common to most of these operations are given in a theoretical section of the symposium: H. HERNE (National Coal Board) dealt with the role of particle inertia in flow round spheres leading to the classical computations of trajectories in potential and viscous flow and of "Collection Efficiencies". PROFESSOR P. R. OWEN (University of Manchester) elucidated the mechanism of particle deposition through a turbulent boundary layer. It is particularly fortunate that the effect of surface properties and surface forces is included in separate contributions to the symposium, since they were ignored in most of the experimental and theoretical work presented.

An appendix is added by that veteran in this field, C. N. DAVIES (School of Tropical Medicine, London), on a critical assessment of the dimensionless group which characterises trajectories of particles subject to Stokes Law of resistance and in dynamically similar flow fields. Throughout the papers this criterion has been severally referred to as Stokes Criterion or Number, Particle Parameter, Impaction Parameter, Inertial Parameter, and DAVIES himself calls it the Particle Resistance/Inertia Parameter. There is much unifying to be done in this field and a useful start could be made by calling this constant the *Albrecht* number, after the first person who published work on this problem in 1931* and who seems to have used it first.

PAUL EISENKLAM

* ALBRECHT, F. *Phys. Z.*, 1931, **32**, 48.

Concepts of Thermodynamics
by E. F. Obert
McGraw-Hill Book Co. Inc., New York, 1960, 528 pp., 85s. 6d.

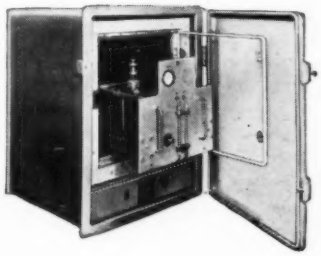
MANY mechanical engineers find, as a result of becoming "process engineers" (described in German as *Verfahrensingenieure*), that the knowledge of thermodynamics they require is no longer limited to "heat engines", but involves a general study of the thermodynamics of flow processes. OBERT's new text-book in the McGraw-Hill Mechanical Engineering Series, *Concepts of Thermodynamics*, emphasises this trend, and makes it very useful for the chief users of process engineering techniques, the chemical engineers.

The book covers, in 16 chapters, the fundamental concepts; temperature and the ideal gas; the first law and the closed system; the first law and the dynamic open system; the reversible process; the second law and topics relating to the second law of thermodynamics; properties of pure substances and p-v-T relationships; general thermodynamic relations for systems of constant chemical composition; the ideal gas and deviations for real gases; mixtures; equilibrium and the third law; basic flow relations and combustion. The treatment of the various topics is balanced and comprehensive. As an example of the general pattern of the book, the chapter on p-v-T relations, this discusses the requirements of an equation of state, and how this is met, in the first instance, by the virial equation. Van der Waals' equation is considered as well as the reduced Van der Waals' equation. Compressibility factors are introduced, with a number of examples explaining their use, and the various other equations of state which have been suggested are discussed and compared. The application of these equations in the evaluation of thermodynamic properties is undertaken, and the chapter concludes with detailed discussion of the principle of corresponding states. The introduction of open systems as a natural extension of the closed cycle at various sections of the text indicates to the student their close relation. Original references are given as footnotes, and each chapter is followed by further selected references and a large number of problems.

Some purely chemical topics like the thermodynamics of solutions and electrochemistry have, of course, been omitted or are only briefly mentioned. This is a book to be seriously recommended to the advanced or honours student in a university degree course, for it will enable him to progress beyond the normal lecture material. Considering the value of its material, its clear presentation, the standard of printing, illustration and binding, the book is not unduly expensive.

W. STRAUSS

Process Analyser



The Pye Process Analyser is an industrial version of the well-known Pye Argon Chromatograph. By utilising an argon ionisation detector instead of a katharometer or thermistors, it achieves an outstanding performance with high sensitivity and exceptional stability. Its comparatively simple and robust design results in reliability, ease of operation and low overall cost.

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SCIENTIFIC PYE INSTRUMENTS

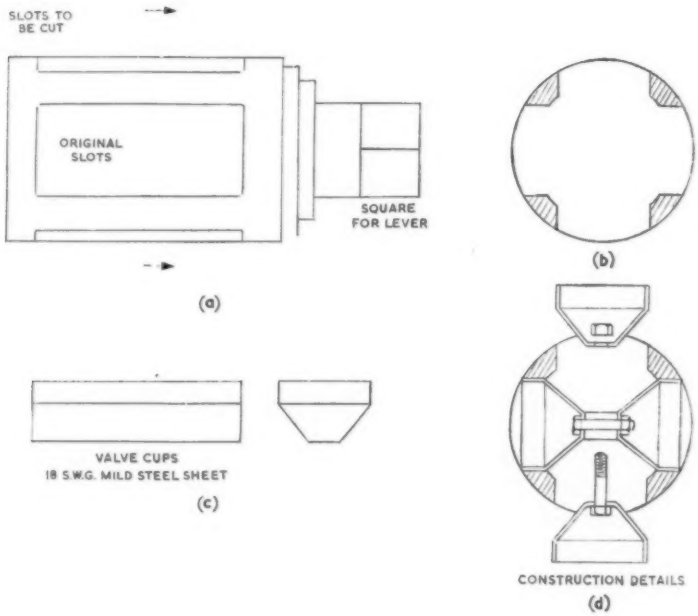
An Improvised Rotary Valve

ROTARY valve manufacturers have produced quite a variety of rotary valves for plant use, but, generally speaking, small-scale valves are made to special orders only.

Recently in some work connected with a pilot process handling granular material a small valve was required to give a controlled variable feed of solids to a pneumatic transport line. As the valve was required urgently, the smooth action of a lubricated "plug cock" suggested that it had distinct possibilities of conversion to a rotary valve of the required size.

The complete conversion was carried out by modifications to the plug only. The case, with its B.S.P. female connections, was fitted directly into the stand pipe.

The plug, as manufactured, was cylindrical in shape, hollow and had two opposite rectangular slots to allow for free passage of material through the cock (Fig. a). A second pair of slots, geometrically similar but at 90° to the original, was cut by drilling and careful filing. Four individual cups were made from 18 S.W.G. mild steel sheet, as shown in Fig. b, and were matched to fit tightly in the slots provided. Two cups were selected, fitted opposite each other, then pulled together by three 2B.A. bolts (see Fig. d). The first two cups were separated by spacing washers so that when the second pair was fitted, in a similar manner, free passage was allowed for the fixing bolts. With the cups clamped together in this way, any protruding metal was filed away, taking care to avoid damaging the plug surface.



The plug was fitted to its case and checked for free rotation. The valve was operated by direct coupling to a variable-speed gearbox driven by a single-phase ¼-hp motor. A simple adaptor was made to fit over the square lever end of the plug.

A 1½-in. B.S.P. plug cock with cup sizes of approximately 2¼ in. long × 1 in. wide × ¾ in. deep gave the following solid delivery rates:

Speed (*rpm*)	*Delivery* (*as coal/hr*)
5	40
10	82
15	114
20	160
25	200

G.O.D. and W.H.N.

Vibrator Motor Maintains Flow in Hopper

A VIBRATOR* motor solved the problem of dislodging material stuck in a hopper handling filter cake at a fertilizer factory.

In this process, filter cake flows from a hopper on to a short feeder conveyor incorporating an electronic probe which indicates whether or not the material is still flowing. Before the vibrator was installed, the detector operated an alarm and an atendant had to climb steps to the hopper platform and hit the sides of the hopper with a hammer.

In the first experiment, a ¾-hp, 3000-rpm vibrator motor was bolted to a ¼-in steel plate of about two its own length, and the complete assembly then bolted at its extreme ends to the side of the hopper about half-way up. The resultant "flapping" effect of the centre of the plate agains the hopper was sufficient to maintain flow of material. A short burst of a few seconds' duration every few minutes was found adequate.

Further experiments were carried out to produce a completely flexible system of operation and in the final installation three methods of control were incorporated:

(a) a manual push-button starter under the control of the operator;

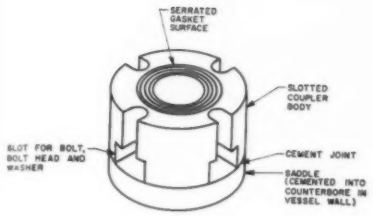
(b) a timer unit which automatically operates the vibrator motor for 10 seconds every 10 minutes; and

(c) a relay controlled by the electronic probe, which operates the vibrator in the event of an interruption of the flow of material between the automatically timed bursts.

These three methods of control are connected in parallel and are, therefore, supplementary. The installation maintains the flow of material without attention.

* The vibrator motor was manufactured by the English Electric Co. Ltd., to whom we are indebted for this item.

Impervious Carbon and Graphite for Aqueous Hydrofluoric Acid


SERRATED GASKET SURFACE
SLOTTED COUPLER BODY
SLOT FOR BOLT, BOLT HEAD AND WASHER
CEMENT JOINT
SADDLE (CEMENTED INTO COUNTERBORE IN VESSEL WALL)
(a)

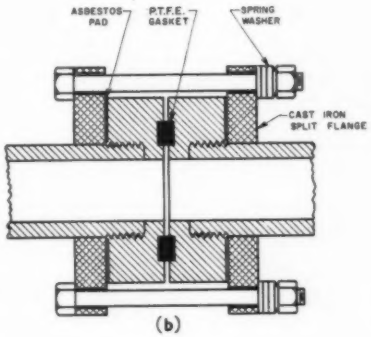
THE handling of aqueous hydrofluoric acid, provided adequate measures are taken, can be carried out successfully by means of improvised graphite equipment. This point is brought home by an account of a plant for condensing, distilling and vaporizing this highly corrosive acid. The design of the vessels including the 32 in. diameter bubble cap distillation column required for separating water and 38 per cent HF is such that, except for piping connections, the impervious graphite is maintained in compression.

The connections used were of the flange type and were slotted for easy assembly of the split flanges used on the pipework (Fig. a). The entire piping system was designed of impervious carbon and graphite piping, the pipes in sizes 1 through 4 in. being constructed of impervious carbon with a fibre glass-epoxy resin armour on the outside. The pipe runs were connected by either flange or cemented joints. The flanged connections were made by cementing a collar to the end of a pipe and connecting with the end of another pipe by means of split cast iron flanges of the type shown in Fig. b.

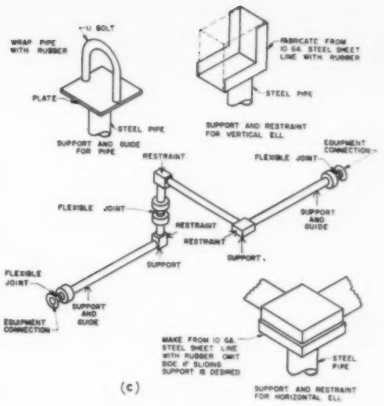
In the case of pipe sizes 6 in. and over plain impervious graphite was used. Cemented fittings were used in all cases. The flange connections were made by cementing collars to the ends of pipes and drawing together by means of split cast iron flanges.

To prevent stressing of the pipe through expansion and contraction, a liberal number of PTFE expansion joints were fitted. These required proper supports and restraints to prevent deflection of the pipework under internal pressure or through internal pressure forces. A typical layout for a section of such piping is shown in Fig. c.

Valves used in the system were of the diaphragm type, and for service in excess of 88°C the bodies were machined from impervious graphite and the diaphragms were PTFE. For lower temperatures the valve bodies were saran-lined steel and they were equipped with diaphragms.



(b)



(c)

For jointings full-faced PTFE plain or envelope gaskets were widely employed for temperatures above 88°C and at lower temperatures vinyledene chloride copolymer rubber (saran) gaskets. In the installation described it is pointed out that it was not possible to use flange connections everywhere in the system. It is recommended, however, that the flanged joint should be such that the joint area allows a comprehensive force of 2000 psi to be applied to the PTFE. In addition, the joint should be restrained so that it would not flow radially and thereby release the bolt loading. This requires a double-groove flange connection with a fairly thick gasket of the type shown in Fig. b.

For cementing, a furan-based, air-curing type was found to give the most consistent results and was also the easiest to use.

So far as the piping system is concerned, the accent is on its careful design. Subsequent experience showed that PTFE-lined steel pipework was suitable for temperatures above 88°C and saran-lined pipe satisfactory at lower temperatures.

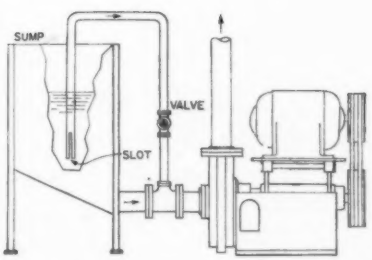
Contributions Invited

The Editor invites contributions to "Process Engineer's Notebook". They should preferably deal with practical devices designed to overcome problems for which standardized equipment is not available; hints for the improved design of conventional equipment; methods of improving equipment operation; safety devices; etc. For the most meritorious contribution the sum of **10 gns.** will be paid, while other contributors will receive **5 gns.** They will be published anonymously or under the contributor's name, according to his wishes.

Overcoming Variable Feed to Pump

A SIMPLE method of overcoming fluctuating feed rates to a centrifugal pump consists of fitting a branch at a point near the pump suction and leading it back into the feed sump. As illustrated, this pipe projects downwards into the slurry to a depth of about 2 ft of the suction intake. The immersed end has two slots cut in it.

When the slurry level in the sump drops below the top of the slots, air is drawn through the side branch into the pump and the pumping rate decreases. The amount of slot uncovered controls the amount of air drawn into the pump. As the level continues to drop, more air is sucked into the pump and its discharge rate continues to decrease. When the level in the sump rises the slot becomes completely submerged and the pump then gives its full discharge rate.



This simple method is satisfactory provided the fluctuations and feed are not excessively wide.

(Courtesy of Denver Equipment Co.)

EROSION RESISTANCE OF MATERIALS OF CONSTRUCTION

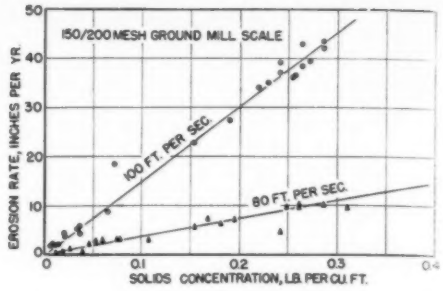


Fig. 1.

A RECENT paper* points out that neither hardness nor strength are adequate criteria of erosion resistance and, in dealing with the wear resulting from the contact and impact of high-speed fluids on solid surfaces, draws attention to the many variables that are involved in this type of attack for which the term "particulate erosion" is suggested.

The factors affecting erosive wear are the nature of the particles, the dynamics of the fluid system, the concentration of particles, their velocity and the angle of impingement.

The paper reports the results of investigations carried out by means of bench-scale "sand-blasting" equipment.

The erosiveness of several solids, relative to silica-alumina cracking catalyst, on SAE 1010 steel was:

Ground mill scale	11.5
Silica sand	4.5
Iron powder	1.4
Used silica-alumina cracking catalyst	1.0
Used molybdena reforming catalyst	0.5

Particles 90 μ in mean diameter gave the highest erosion rate. Particles 180 microns were 30 per cent less erosive and those 60 microns only slightly less erosive.

Dynamic Factors

Test-work in full-scale units indicates that erosion is proportional to particle concentration throughout the range of operation (Fig. 1). At high concentrations, however, interaction effects reduce the linear relationship. Fig. 2 shows that erosion varies with a high power of the fluid velocity (average 3.7).

Particles striking normal to the wearing surface produce a deformation wear similar to "peening". Brittle materials fail readily under this type of attack; ductile materials, particularly those having low work-hardening tendency, give better results.

Particles striking the surface at an angle have components parallel and perpendicular to the surface. Materials that resist cutting or machining are desirable here and brittleness is not an adverse factor. Fig. 3 shows laboratory results obtained on two types of materials with commercial regenerated silica-alumina cracking catalyst. Carbon-steel has low resistance to cutting action and the wear rate is a maximum at 55°. The cobalt-base alloy has extremely high resistance to cutting. Most materials exhibit curves similar to one or the other of these two. Generally, carbon steels, austenstic steels, low-alloy steels and ductile materials have curves similar to carbon steel. The other curve is characteristic of sintered tungsten carbide alloys and some hard-facing materials.

Correlations

Correlations of erosion resistance of metals with commonly measured physical properties were attempted. None is dependable enough to serve as a means of predicting performance. Melting point and elastic modules correlated better than other variables and the ratio of these two, for a number of alloys and pure metals, was better than either alone (Fig. 4). However, the correlation is of limited use because the m.pt. is ill defined for composite sintered materials.

* Paper presented to the 44th A.I.Ch.E. Conference, entitled "Erosion Resistance of Materials of Construction", by William Bulkley.

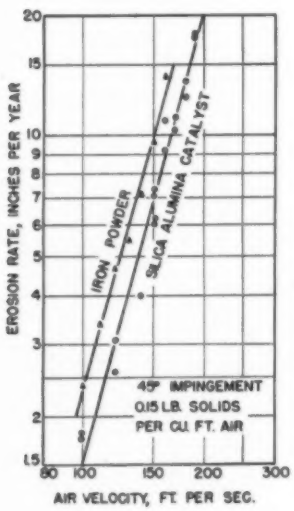

EROSION RATE, INCHES PER YEAR
IRON POWDER
SILICA ALUMINA CATALYST
45° IMPINGEMENT
0.15 LB. SOLIDS PER CU. FT. AIR
AIR VELOCITY, FT. PER SEC.

Fig. 2.

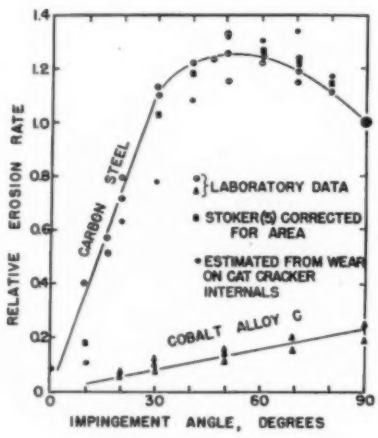


Fig. 3.

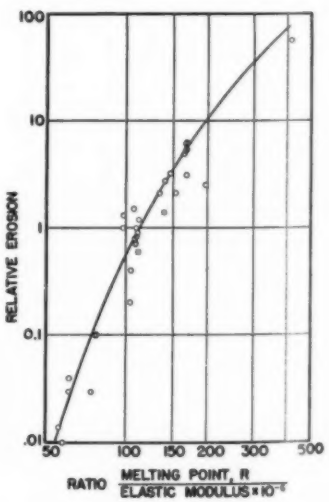


Fig. 4.

MEET AN ION EXCHANGE RESIN

Not very impressive? Yet these resins can prevent **SCALE** in boilers . . . **CORROSION** in pipes . . . **SILICA** deposits in turbines . . . as well as the effects of **HARDNESS** in water everywhere. If you have need to deionize, soften, dealkalize or deacidify water then you must use Amberlite Ion Exchange Resins. Why not discuss the problem with our technical staff? Meanwhile, for a better understanding of Ion Exchange, write for 'If you use Water'—a 24-page descriptive booklet. This gives basic information on ion exchange treatment of water . . . and is, of course free.

AMBERLITE ION EXCHANGE RESINS

CHARLES LENNIG & COMPANY (GREAT BRITAIN) LTD

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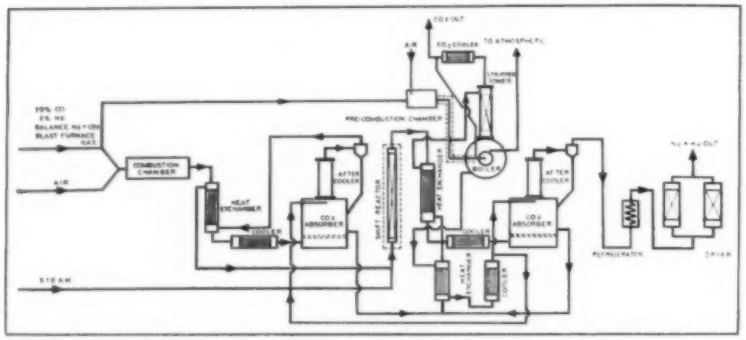
Chemicals for Industry

AMBERLITE *is a registered trade mark of our parent company Rohm & Haas Co., Philadelphia.*

AP 64

PLANT EQUIPMENT NEWS

Production of N_2 H_2 Mixture



A new process which uses blast furnace gas to produce a N_2/H_2 mixture containing 1-8 per cent H_2 is reported. This gas is replacing coke oven gas in the heat treatment of steel, since it provides an inert atmosphere for bright annealing and does not form soot during cooling.

The plant is continuous, designed for minimum shut-down and requires the part-time services of one man.

Blast furnace gas, 30 per cent CO, is partially burned through a specially designed burner, firing into a well-insulated refractory-lined chamber. The gases are cooled to ambient temperature and CO_2 is removed in an absorber using ethanolamine solution.

Gas leaving this unit is 92-99 per cent N_2 and 1-8 per cent CO. Steam is added and gases enter the shift reactor, where CO is converted to CO_2 and an equivalent volume of H_2 is formed.

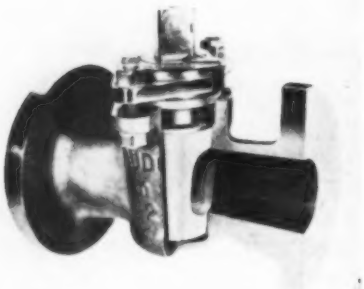
CO_2 is removed in a second absorber and wet H/N mixture leaves the plant. Drying is effected by cooling the gas through a refrigerator unit and passing it through an Incandescent desiccant dryer.

Basic designs cover 10,000, 25,000, 50,000 and 100,000 scfh units, although any size will be manufactured to customers' requirements. **Gas Atmospheres Division, The Incandescent Heat Co. Ltd., Smethwick, England.**

BCE 9641 for further information

Audco Valves with PTFE Sleeved Plug

Audco valves with PTFE taper sleeved plugs are now available. The properties of PTFE are well known and its use as a plug has produced a valve which is leak-proof, requires a low turning effort and is virtually maintenance free. Galling and metal-to-metal sticking has been eliminated.



Valves in cast iron, Audcoloy and stainless steel are available for selective use on severely corrosive services. Sizes are ½ in., ¾ in., 1 in., 1½ in., 2 in., 2½ in. and 3 in. **Audco Engineering Co. Ltd., Newport, Shropshire.**

BCE 9642 for further information

Piston Pumps

Keelavite Hydraulics announce a complete range of high-pressure hydraulic equipment comprising a series of fixed-capacity piston pumps and complementary control valves for high-pressure systems.

The piston pumps have either three or six pistons and are available in nine basic sizes, but by varying the piston bore and stroke a total of 22 different volumetric outputs can be obtained, in the range 0.28 to 44 gpm. The maximum pressure attainable is 7100 psig.

In addition to the pumps, which have an average volumetric efficiency of 94 per cent, control valves in sizes ½ to 1¼ in. BSP as well as relief and off-loading valves can be supplied. **Keelavite Hydraulics Ltd., Allesley, Warwicks.**

BCE 9643 for further information

Rapid Coupling for Polythene Tubes

It is possible for an unskilled person to couple two pieces of polythene tubing in a matter of seconds by means of a simple line coupling. An outstanding advantage is that the joint can be as easily dismantled as it can be assembled. An important feature of the coupling is a stainless-steel spring which grips the tube around its circumference. This allows the tube to be pushed into the fitting to give an absolutely leak-proof joint by the mere twist of its locking nut.

These fittings are marketed under the name "Tubelock" and are used with ½-in. or ¾-in. polythene tubing. Their use provides considerable flexibility in the layout of pipework, since their ease of removal and reassembly makes rapid modification possible. **Hozelock Ltd., Haddenham, Bucks.**

BCE 9644 for further information

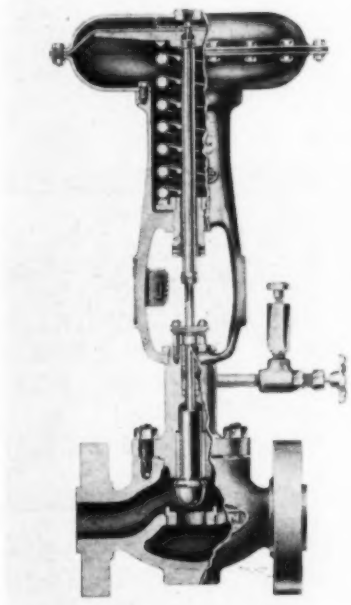
Marine Pressure Jet Register

This register is unique in not relying upon a quarl for its operation. Stabilization is effected by the vortex caused by the radical swirler in the primary air section. Complete and rapid combustion is ensured by directing the secondary air into and along the cone of the oil spray. No vital part of the air director is exposed to the flame and thus no damage can occur due to back radiation. No adjustment of the air register is required during operation. A shutter running on the carrier tube serves to isolate the register from the boiler windbox. **Hamworthy Engineering Ltd., Poole, Dorset.**

BCE 9645 for further information

Diaphragm-operated Control Valve

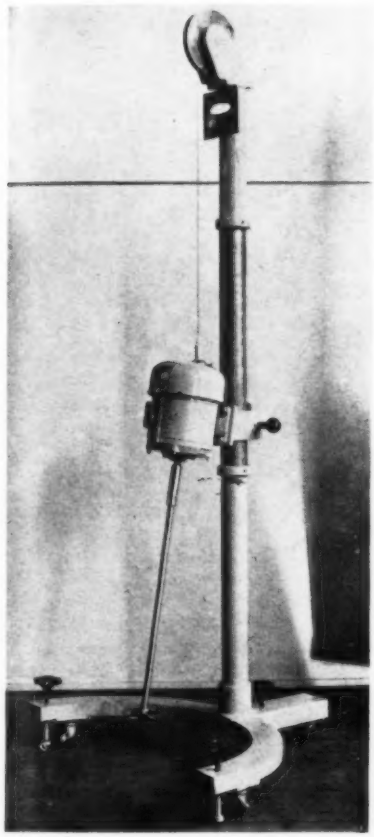
A completely new range of Masoneilan single-seat heavy-duty diaphragm-operated control valves is now available. They are available screwed ¾ in.-2 in. with trim sizes ¼ in., ⅜ in., ½ in., ¾ in., 1½ in., 2 in. and flanged ¾ in.-10 in. with not less than four trim sizes for each line size



valve. The new valves add the performance characteristics of an angle type control valve to the advantage of the simplified pipework of a straight-through type of body. **Crosby Valve & Engineering Co. Ltd., Crosby Works, Ealing Road, Alperton, Wembley, Middlesex.**

BCE 9646 for further information

Mobile Adjustable Mixer



This adjustable mixer, costing £120, is driven by a ½-hp motor and has a stainless-steel shaft and propeller. It is mounted on a mobile base. **Chemical Equipment Engineering Ltd., Castle Street, Macclesfield.**

BCE 9647 for further information

Cladded PVC Ducting

The technique of providing rigid PVC with an external cladding of glass-reinforced polyester resin makes possible the combination of high chemical resistance of rigid PVC with the strength and temperature resistance of reinforced resin. The use of resin/glass cladding eliminates the need for extensive stiffening and results in a lighter product.

Ducting produced in this way is fully protected with a final coating of Nutracote vinyl and is highly resistant to corrosive chemicals and fumes. **Tanks & Linings Ltd., Droitwich.**

BCE 9648 for further information

Automatic Forced-draught Packaged Gas Burner Unit

Built for town gas with a calorific value of 500 Btu/cu ft at 2 in. W.G.

Five models cover a gas consumption range of 265 to 10,700 cu ft/hr with a heat output of 10^5 to 4×10^6 Btu/hr respectively.

The burners will operate at a negative draught of 0.1 in water gauge at the front plate, subject to the chimney dimensions being adequate for the evacuation of the gases. The main gas jet is integral with the casing, housing a directly driven fan actuated by an externally mounted electric motor.

The gas pressure governing device, the gas pilot jet and the flame failure control are fixed to the smaller models. For the larger sizes they are applied to the pipework adjacent to the burner.

Due to fully automatic operation under thermostatic control combined with high/low flame modulating control when this is used, the gas consumption is as economical as possible and strictly in accordance with the heat demand. The burner controls ensure that operation is to rigid standards of safety. **Prior Stokers Ltd., Prior Works, 1-3 Brandon Road, York Way, London, N.7.**

BCE 9649 for further information

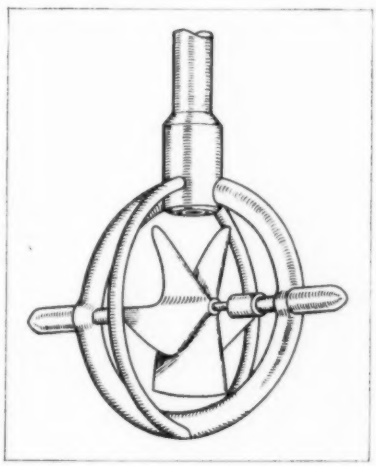
Reinforced Plastics Storage Tanks

These are now available for long-term storing of corrosive and radio-active liquids. They were originally developed for the A.E.R.E. at Harwell. The tanks are rectangular, jointless and comprise a double-skin, foam-filled structure capable of overcoming large deflections under heavy load. They are easily handled and capacities range from 500 to 2400 Imp galls. **Bristol Aeroplane Plastics Ltd., Filton House, Filton, Bristol.**

BCE 9650 for further information

Miniature Current Flowmeter

This miniature instrument will measure very low rates of flow of liquids in very small ducts and hydraulic models. It will measure flows as low as 0.9 in./sec and as high as 5 ft/sec. The measuring head consists of a five-bladed PVC rotor mounted on a tungsten spindle; measurement is with electronic equipment using a Wheatstone bridge network supplied from a 10 Kc/s oscillator. Size of the head to be submerged (illustrated) is 15 mm × 25 mm × 15 mm. **Armstrong Whitworth Equipment, Hucclecote, Gloucester, England.**



BCE 9651 for further information

Dewpoint Measuring Unit

A new dewpoint measuring unit with a range down to −150°C is illustrated. For permanent installation, it is designed to measure moisture in dry gas or air lines.

A small amount of gas is passed through the unit which contains a replaceable ceramic filter. It is very simple and no attention is required. It is suitable for almost all gases and costs £10. **Shaw Moisture Meters, Rawson Road, Westgate, Bradford, Yorks.**

BCE 9652 for further information

Viking Pumps

Viking positive-displacement pumps operate on the "gear-within-a-gear" principle and have only two moving parts. Capacities range from ⅓ gpm to 1050 gpm. These are now made in the U.K. by **Zwicky Ltd., Buckingham Avenue, Slough, Bucks.**

BCE 9653 for further information

PLANT EQUIPMENT NEWS

New Variable-speed Gears

Two important new additions to the Carter range of hydraulic variable-speed gears have been announced. The size AM26 gear (illustrated) incorporates the original torque sharing positive-displacement hydro mechanical design. This gear, together with the restyled size FLO gear, will be demonstrated at the Engineering, Marine, Welding and Nuclear Energy Exhibition in London (April 20 to May 4). **Carter Gears Ltd., Thornbury Road, Bradford, 3, Yorks.**

BCE 9654 for further information

Variable-speed Blender

Variable-speed motors, with remote control dials, have been introduced in a "Blender" volumetric feeder system.

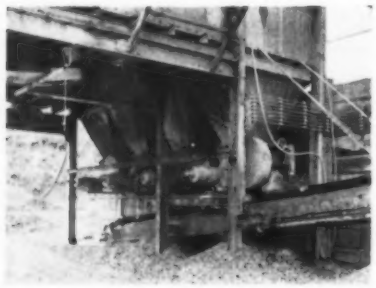
Material falls down a hopper through an adjustable gate and the flow is controlled by rotating paddles driven at variable speeds. Combinations of speed and door settings provide a range of outputs from 5-200 tons/hr per Blender. Blenders are mounted singly or in banks. Operation, covering the full range, is controlled from a remote control desk which has a speed indicator dial (0-100) for each Blender; a pre-set dial (0-100 per cent); a selector switch for each Blender; and a pre-set operation timer.

When installed, all Blender gates are set so that a similar tonnage passes from each in a given period. This setting is not disturbed during operation.

To operate the system, the pre-setting dial is turned to the percentage required from each Blender; i.e., No. 1 Blender at 25 per cent, No. 2 Blender at 30 per cent, No. 3 Blender at 45 per cent. The pre-set timer is then set according to the time which the whole operation will take. The "start" button is pressed and blended aggregate of the required composition flows continuously for the specified time.

Specification changes are made by changing percentage readings on the pre-set dials. Batch volumes are altered by increasing or reducing delivery time. **Frederick Parker Ltd., Leicester, England.**

BCE 9655 for further information



M.H.R. Miniature Flow Inducer

A miniature peristaltic pump based on the design of the original Watson-Marlow H.R. flow inducer.

An elastic tube is clipped to a multi-curved track, concentric with a rotor bearing three rollers. As the rotor goes round, the rollers pass over the tube, flattening it against the track. This "flat" moves around the central part of the track, driving anything in the tube before it. At the same time, the restitution of the tube behind the roller creates a suction, drawing in more fluid to be pushed by the following roller.

Direction of flow and speed are controlled by a single knob on the top of the unit. Maximum pressure head against which the unit will work depends chiefly on the bore of the tube used. Operating parts are lubricated for life. The rollers are of nylon with molybdenum disulphide and are thus self-lubricating. The unit produces no shear or heat to damage the most delicate of fluids.

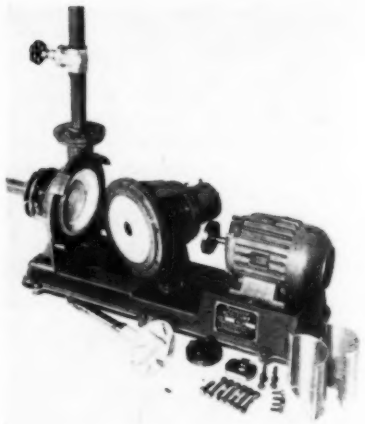
The M.H.R. flow inducer is built as standard for tubes $\frac{1}{16}$-$\frac{5}{16}$ in. bore and tubes are available to handle any liquid or gas in common use. **Watson-Marlow Air Pump Co., Marlow, Bucks.**

BCE 9656 for further information

Ceramic Acid Pumps

The illustration shows a TransKem TK ceramic pump.

The pump casing is split vertically; the front part is cast integrally with the inlet and outlet flanges and supporting feet. The rear half of the casing, carrying the impeller shaft and bearings, can be readily unbolted and swung round on the bed plate exposing the impeller for inspection or renewal without disturbing the bearing arrangement or disconnecting the pipelines.



TK pumps will give excellent service under the most severe corrosive conditions. Sales inquiries to **TransKem Pumps Ltd., Sunlight House, Quay Street, Manchester, 3.**

BCE 9657 for further information

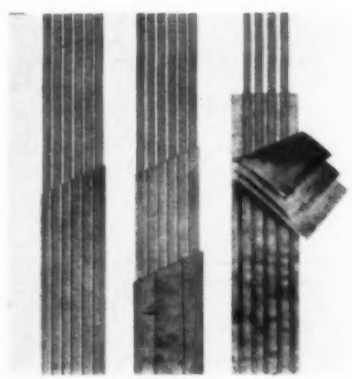
Mercury Cleaner

The cleaner, consisting of a Perspex body and cup with a central well through which the mercury is decanted into a storage jar beneath, will handle 2-3 lb of mercury a minute. In the well is a gold seal, which, when wet with mercury, forms a positive seal through which suspended contaminants cannot pass. Price £4 18s. **Loughborough Glass Co. Ltd., Loughborough, Leicestershire.**

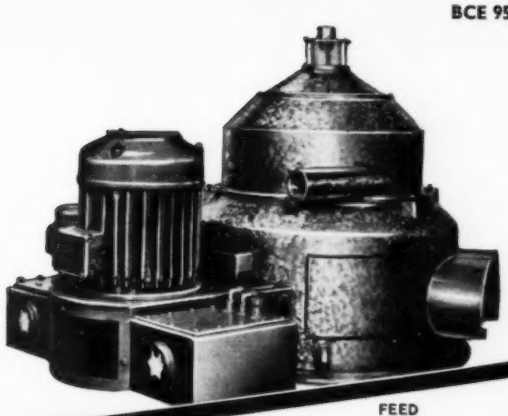
BCE 9658 for further information

Hot-foil Flat-element Heating Tapes

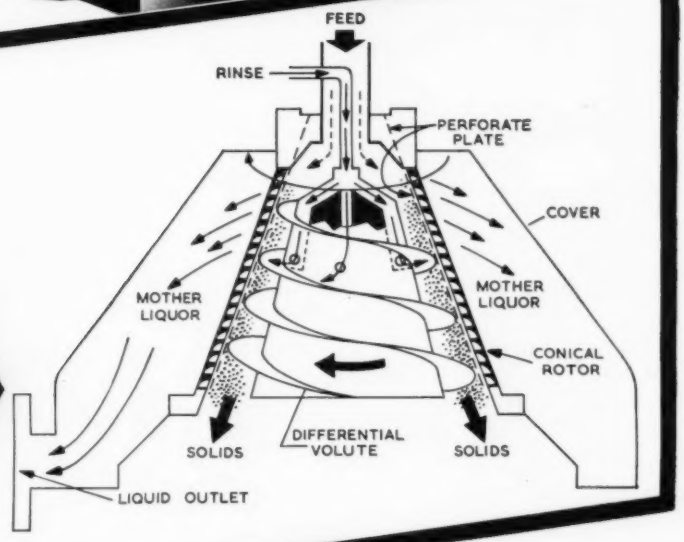
This is the invention of Dr. Paul Eisler, who originated the printed circuit. With these flat element types there is a very small difference in temperature between the element itself and the heated object. Elements are of thin metal foil, and in one type six are laid in a tape 1 in. wide and insulated with a high-temperature polyester resin; three-quarters of the tape surface are heating surface; loadings up to 15 watts/sq. in. are possible.



BCE 9597 for further information



Now the **Super-Screen** joins the Sharples range



The arithmetic of success

A well proved Centrifuge pioneered in the European chemical and process industries – + Sharples manufacturing and chemical engineering experience = The New Sharples Super-Screen

This is important news for everyone in the process industries. You can now have the best of both worlds. Installations in many parts of the world testify to its proven application on crystalline materials, but already our development men have found many exciting new applications. Write to-day for further information on this new centrifuge or about your own separational problems.

SHARPLES

The Sharples range will be on show at the Achema Exhibition in Frankfurt, Hall No. 3 – Booths B22/24 and A23 June 9th – 17th.

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PLANT EQUIPMENT NEWS

Industrial applications include frost protection and the heating of almost any type of fluid in pipes, tanks and other containers. Such fluids include oils, waxes, paints, bitumen, fats, chocolate and low melting point metals. A number of specialized operations, such as heating contents of road tankers, objects of irregular shape, etc., are possible. Hot-foil mantles, for heating valves and similar equipment, are also available. **The MEI Co. Ltd., Upper Villiers Street, Wolverhampton.**

BCE 9659 for further information

Resin Armour Coating

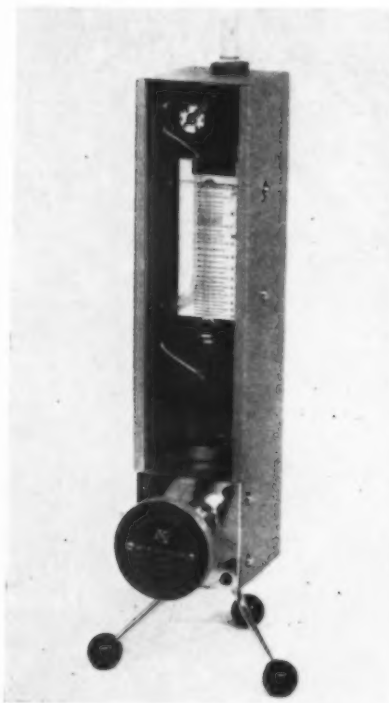
A tough armour-like coating with exceptional resistance to abrasion, ultra-violet rays, chemicals and weather has been developed by The Goodyear Tyre & Rubber Co. from polyester resins. The VPE 200 coating can be applied by spraying, dipping, roller coating, brushing, hot melt and knife coating. It is most suitable as a protective coating applied to metals. Other advantages include excellent adhesion, clarity, electrical properties and the ability to bind pigment. **Hubron Sales Ltd., Failsworth, Manchester.**

BCE 9660 for further information

McLeod Gauge

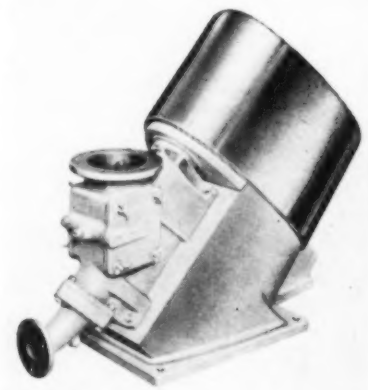
An entirely new method of operation which eliminates the need for a secondary vacuum pump is incorporated in this McLeod gauge.

A vacuum balanced piston is used to displace the mercury into the glass gauge head. The balancing vacuum on the piston is maintained via a second leg of the gauge head connected to a point above the top level which the mercury can reach. Operation of the gauge is controlled by a handle which is turned through approximately 90° to raise the mercury to the level necessary for measurement. On release of the handle the mercury automatically returns to the lower position ready for the next measurement. **N.G.N. Electrical Ltd., Accrington, Lancs.**



BCE 9661 for further information

Mono Junior Powder Pump



A small, compact, powder pump has been developed for small batch transfers. This unit has been used effectively for the metered dosing of anti-pest powders to grain before storage. **Mono Pumps Ltd., Mono House, Sekforde Street, London, E.C.1.**

BCE 9662 for further information

Hestair Compressor

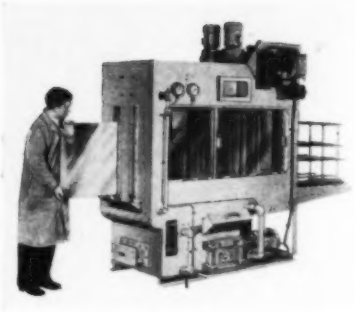
Small air-cooled compressor developed for general compressed air duties with free air deliveries from 10-25 cu ft/min (17-43 cu m/hr) and pressures up to 350 psi (24.5 kg/cm²). Two sizes are available but, apart from the cylinder barrel and piston, all parts are interchangeable. A sheet-metal shroud directs air on to the cylinder and head. Concentric type suction and delivery spring-loaded plate valves are fitted. **Hamworthy Engineering Ltd., Poole, Dorset.**

BCE 9663 for further information

"Perspex" Sheet Washing and Drying Machine

This machine is designed to remove swarf, sawdust and residual gelatine from plastic sheets which must be completely free from soilage. In addition, a de-statting agent in the washing solution neutralizes static charges. Sheets $\frac{1}{16}$ in. to $\frac{1}{4}$ in. thick are handled without adjustment to the machine.

The machine operates two wide. Sheets



are fed edgeways, through the vertical slats, into guide rollers, which are covered in soft rubber and "Terylene" dry felt. Both roller systems are independently driven.

As they pass between the rollers, the sheets are washed on both sides with recirculated solution at 125-135°F, delivered through a series of vertical jet tubes, and dried.

At the exit, sheets are stacked automatically. **Dawson Bros. Ltd., Gomersal, near Leeds.**

BCE 9664 for further information

Horizontal Split Casing Pumps

Medium-pressure horizontal pump designed for public water supply, power station and refinery circulation, dry docks, etc. Capacities from 800-8000 igpm (11,000-36,500 litres/min) and heads from 10-180 ft (3-55 metres). An efficient, compact pumping unit which provides maximum accessibility for removal and inspection of the rotating element. Suitable for any method of drive and variation in glands, bearings, etc., to meet particular pumping conditions. **Hamworthy Engineering Ltd., Poole, Dorset.**

BCE 9665 for further information

Cheap Closed-circuit Television Camera

Production control, material handling, dangerous viewing, process control and centralised record viewing are just some of the applications claimed for the new "Neveye" closed-circuit television camera. Costing only £124 19s. (lens extra) and designed to work direct to any domestic receiver, it should be popular with small firms who hitherto have not been able to afford such equipment. It weighs 12 lb and measures 11¼ in. × 5½ in. × 6¼ in. As illustrated, it is fitted with a lens turret for wide angle and telephoto shots.

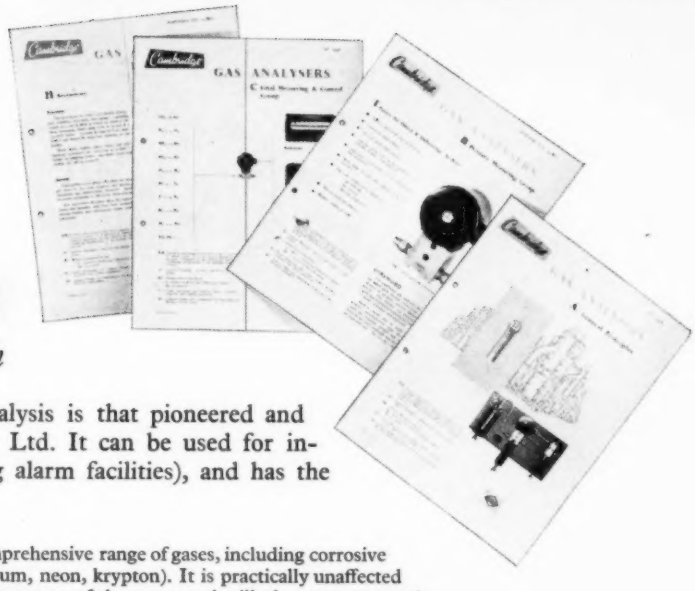
Nottingham Electronic Valve Co. Ltd., East Bridgford, Notts.

BCE 9666 for further information

Cambridge

GAS ANALYSERS

for Industry and Research



The most economical method of gas analysis is that pioneered and developed by Cambridge Instrument Co. Ltd. It can be used for indication, recording and control (including alarm facilities), and has the following advantages:

It can be used to analyse a very comprehensive range of gases, including corrosive (HCl, Cl_2, SO_2) or inert (argon, helium, neon, krypton). It is practically unaffected by the rate of flow, pressure, or temperature of the gases, and will also measure static gases. The equipment is accurate, but robust. The method is electrical, simple, flexible and reliable. It is direct reading (or recording), and the analysis is continuous. It is easy to install, and the indicator (and/or recorder) may be any reasonable distance from the measuring unit. Intrinsically safe circuits are available for dangerous working conditions.

Send for the publications illustrated above (AR144). For future publications (another section of List 144 is still to be published) send for Mailing Form AR/5/61.

CAMBRIDGE INSTRUMENT COMPANY LIMITED 13 Grosvenor Place, London, S.W.1

For HIGH TEMPERATURE FLUID HEAT TRANSMISSION or DIRECT HEATING of PROCESS LIQUIDS

either ORGANIC, INORGANIC, ACID OR ALKALI, any of which can contain SOLIDS

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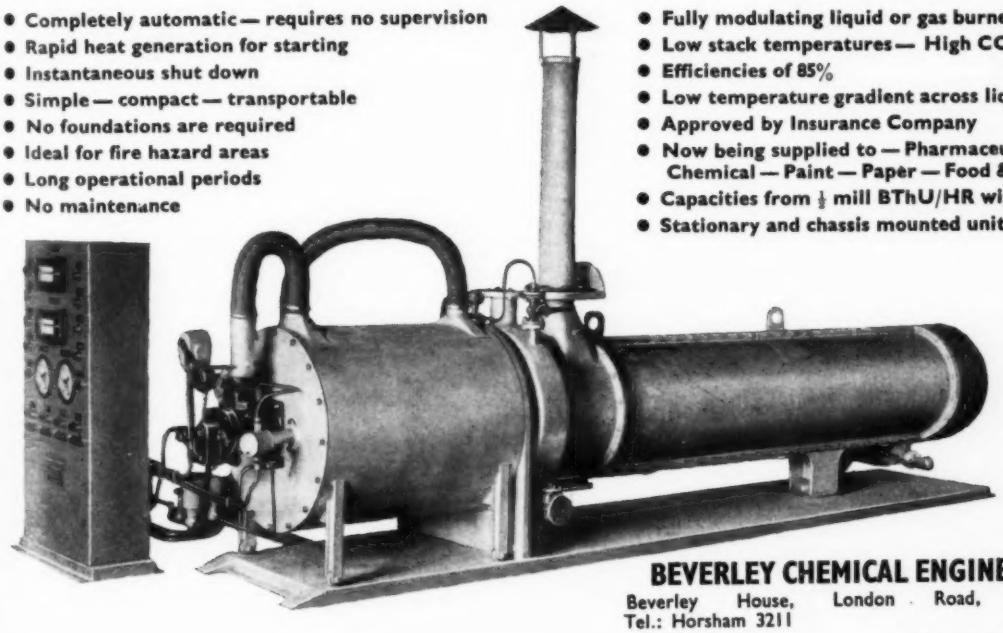
- Completely automatic — requires no supervision
- Rapid heat generation for starting
- Instantaneous shut down
- Simple — compact — transportable
- No foundations are required
- Ideal for fire hazard areas
- Long operational periods
- No maintenance

- Fully modulating liquid or gas burners
- Low stack temperatures — High CO_2
- Efficiencies of 85%
- Low temperature gradient across liquid film
- Approved by Insurance Company
- Now being supplied to — Pharmaceutical — Heavy Chemical — Paint — Paper — Food & Tar Industries
- Capacities from ½ mill BThU/HR with 5.1 turndown
- Stationary and chassis mounted units



Delivery: 10 — 12 weeks

Send for specifications to:

BEVERLEY CHEMICAL ENGINEERING Co. Ltd.
Beverley House, London Road, Horsham, Sussex
Tel.: Horsham 3211

BCE 9599 for further information

PLANT EQUIPMENT NEWS

"Clayton-Still" Heat Exchange Surface

This exclusive heat exchanger, which will be exhibited at the forthcoming exhibition at Olympia, is shown in the illustration. A very high coefficient of heat transfer is claimed. There is no standard tube, and special demands can be met by the simple alteration of surface ratios, loop width and height, winding density, tube and wire gauges and method of bonding.

Materials may be copper, copper alloys, brass, steel, etc. Copper or copper alloy tubes can be bent to almost any shape.

Bonding of wire to tube is by soft soldering, induction brazing or by hot-dip galvanizing.

Two special types of tube with extended inner surfaces have been evolved for cooling oils and similar liquids. **Clayton Dewandre Co. Ltd., Titanic Works, Lincoln.**

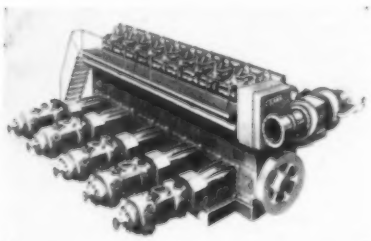
BCE 9667 for further information

Compressor for 1500-3000 bhp Range

Clark Bros. Co. announce their new Model TBA gas-engine-driven compressor for the 1500-3000 bhp range.

It will be built in 5, 6, 8 and 10 power cylinder models rating at 1500, 1800, 2400 and 3000 bhp respectively. These sizes, combined with TLA units rated at 1700, 2000, 2800 and 3400 bhp, offer a full range of models.

TBA operating characteristics are the same as the Model TLA, except that it is a shorter stroke machine and a full-flow 5-micron oil filter has been added to the system.



The Clark-designed turbo-charger is jet air started, fully automatic and completely self-sustaining at normal operating speeds. The turbocharger system is coupled with a new automatic ignition timing control, making TBA suitable for variable speed/variable load applications. The fuel consumption curve remains essentially flat over a wide range.

It is available for purchase in sterling throughout the world. **Clarke Bros. Co., 197 Knightsbridge, London, S.W.7.**

BCE 9668 for further information

New Publications

Titanium for Textile and Paper Pulp Bleaching

This 10-page illustrated brochure describes the use of titanium in components used in bleaching equipment. Titanium is completely resistant to boiling sodium chlorite and hypochlorite solutions in all concentrations, and to hot chlorine dioxide vapours generated during chlorite bleaching. The rate of attack in other bleach liquors, such as calcium hypochlorite, peroxide bleach liquor and sodium chlorite/pyrophosphate mixtures, is less than 0.005 in. a year.

I.C.I. titanium is available as sheet, strip, plate, rod, extruded sections, tube and wire. Increased production over the last five years has reduced the price of titanium by over 50 per cent. **I.C.I. Ltd., P.O. Box 19, Templar House, 81-87 High Holborn, London, W.C.1.**

BCE 9669 for further information

Regulation and Proportioning of Raw Materials for Sinter Plants

An 8-page brochure describes equipment for controlling the supply of the four main raw materials fed to a sinter plant: the lime-silica ratio, the return fines, the carbon-bearing ingredients and the raw mix feed. **Huntington, Heberlein & Co. Ltd., 28-29 Dover Street, London, W.1.**

BCE 9670 for further information

Dechema Brochure

A 16-page illustrated brochure has been published by Dechma (Chemical Engineering Group of the Association of German Chemists) to describe the facilites which that Association provides for chemists and engineers. The brochure is trilingual—English, French and German—and will be of interest to all those who are concerned with chemical engineering and chemical process engineering. It is available free of charge on application to **Dechema, Frankfurt am Main 7, Postfach 7746.**

BCE 9671 for further information

Delrin Acetal Resin

This 23-page brochure describes Delrin —a highly crystalline, stable form of polymerized formaldehyde — which has replaced metals in a host of mechanical structural applications.

Delrin is used for gears, bearings, anti-friction and electrical applications. It is chemically and heat resistant and non-toxic. It can be machined as a metal and handled in injection moulding, extrusion and blow moulding equipment. **Du Pont Co. (U.K.) Ltd., 76 Jermyn Street, London, S.W.1.**

BCE 9672 for further information

Electric Furnaces

An 8-page illustrated brochure showing a variety of electric furnaces for all industries. These include: continuous furnaces, electric melting furnaces, heavy-duty furnaces, controlled atmosphere furnaces and standard units. **Metalectric Furnaces Ltd., Cornwall Road, Smethwick, England.**

BCE 9673 for further information

Two publications from Knapp Mills Inc. described Insmetal shields and lead tube. Insmetal shields are especially designed to resist corrosion and are available in several basic types, all of which are lead surfaced with different metals; they include Bauxilum (lead surfaced with aluminium or alloy), Capralum (copper), Ferrolum (steel), Nicrolum (stainless steel) and Ferro-Nicrolum (nickel alloys). This publication gives details of the corrosion resistance of Insmetals to a wide variety of chemicals, and a large number of pictures showing various applications is included.

Lead-Lube, a leaded grease, is the subject of the second publication. Two types, K and KM, are available and these are described in detail. The lubricant is claimed to give excellent lubrication in the presence of dirt, grit and abrasives; to replace wear by re-surfacing; lubricate efficiently under high pressure; and prevent uneven wear.—**Knapp Mills Inc., 23-15 Bordon Avenue, Long Island, City, 1, N.Y., U.S.A.**

BCE 9674 for further information

A new brochure published by Zwicky Ltd. gives details of the company's range of pressure control and regulating valves for oil-burning installations. There are two types of controlled pressure valve, one reacting to pressure on the outlet side and the other to pressure on the inlet. Although the valves were developed primarily for oil-burning systems, they also have applications in other fluid systems where it is necessary to maintain a constant predetermined pressure. Drawings of both types of valve are shown and the publication includes charts showing flow in gallons per hour.—**Zwicky Ltd., Slough, Bucks.**

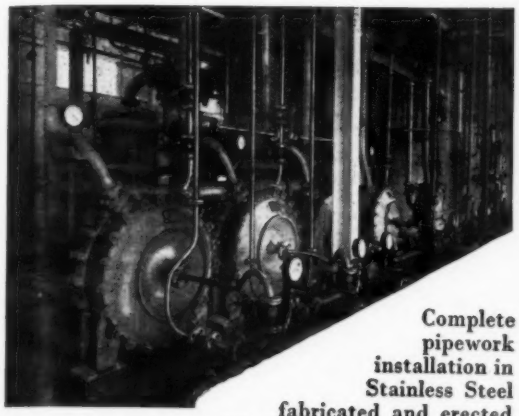
BCE 9675 for further information

A new 32-page booklet from Panellit Ltd. describes the Panalarm audio-visual annunciator in detail. A well-produced publication, it opens by discussing the basic function of annunciators and then goes on to give details of the advantages of the Panalarm system. Most of the publication is devoted to a detailed description of the various models which are available and their special applications. At the end of the booklet the two types of visual signal used in Panalarm systems are described, as well as audible signals.—**Panellit Ltd., Elstree Way, Borehamwood, Herts.**

BCE 9676 for further information

Stainless Steel . . .

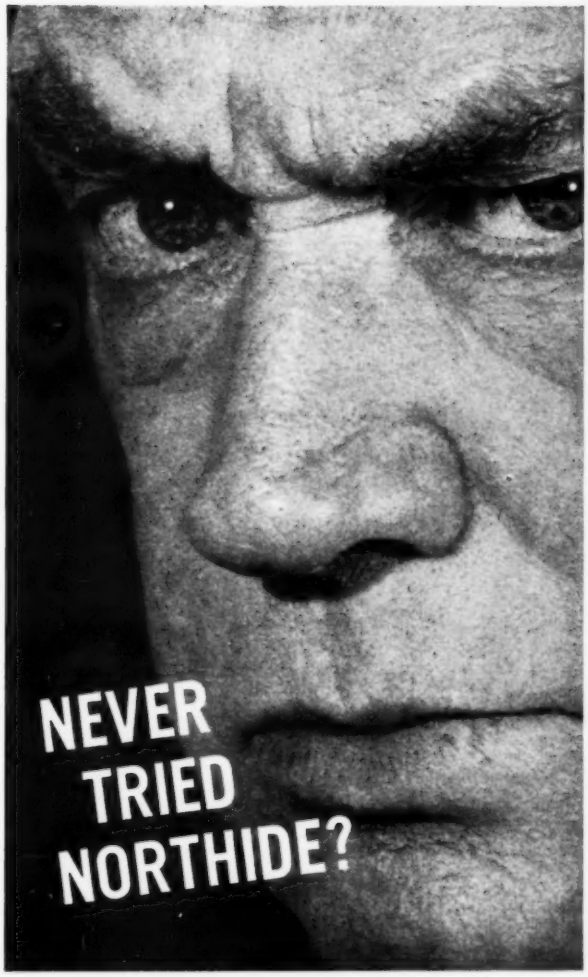
tanks, coils and pipework by *Jenkinsons*



Complete pipework installation in Stainless Steel fabricated and erected on site by JENKINSONS.

Also fabricated and erected on site by JENKINSONS, Stainless Steel ducting 9 ins and 18 ins dia. with special smooth finish both internally, to minimise friction losses, and externally, to improve corrosion resistance.

W. G. JENKINSON LTD.
ARUNDEL STREET; SHEFFIELD 1.
Phone 27438/9



Then, for safety's sake read on...

Northide Limited supply protective clothing for workers in more industries than we have space to mention. Anything that protects anyone from top to toe, we have it. Name it: gloves, garments or goggles: we supply it. So now you know—and now you know, how about writing to us for some free advice and/or free leaflets? Not tomorrow, but today: now.

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NORTH

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World of Chemical Engineering

New Plants Overseas

U.S.A.

Goodrich-Gulf Chemicals Inc., of Ohio, will construct a multi-million-dollar plant in West Virginia for the commercial production of Ameripol CB, cis-polybutadiene rubber as a replacement material for natural rubber in heavy-duty tyre treads. The plant should be in operation before the end of this year and initial output will be 20 million lb annually.

A process for detecting radiation pollution in foods, developed at the University of Nevada, measures accurately the amount of radioactive cæsium in ½ oz of vegetable or animal tissue. Strontium 90 is also recovered in a form so that it may be easily measured.

ARGENTINA

I.C.I.'s subsidiary, "Duperial", is contemplating a 10,000 ton/annum polyethylene plant. Investments are evaluated at £5,760,000.

FINLAND

Rikkihappo ja Superfosfaattitehtaat Oy, a partly state-owned company, is building a 30,000 ton/annum aluminium sulphate plant at Jarjavalta. The plant will process imported aluminium oxide and the sulphate is destined for local consumption.

The company is also considering the installation of a sodium sulphate plant at Kokkola.

SUDAN

The country's first pharmaceutical plant at Khartum which will produce sulphamides, penicillin and vitamins has been installed by the "Sudanese Chemical Industries". This company has also installed cotton seed oil refineries and soap plants at Khartum in 1959 as well as a match making factory with Japanese equipment.

ITALY

Adria Chemie is the name of a company formed for the production of chemicals by local interests in Trieste. A new plant will be erected to produce synthetic resins, plastic synthetic lacquers, nitrocellulose lacquers and glues for the furniture industry.

Montecatini are to build a modern pyrites plant at Follonica. It will be operational in 1962 and will produce 170,000 tons/yr of iron oxide and 350,000 tons/yr of conc sulphuric acid.

JAPAN

A refrigerated L.P.G. tanker, having a capacity of 180,000 barrels, is to be built in Japan for the Bridgestone Liquefied Petroleum Gas Co. Ltd. of Tokyo. The L.P.G. will be carried at −40°F.

ADEN

BP's Aden Refinery is to have its present annual capacity of 5.5 million tons increased to 6.8 million tons a year. No new processing units will be required.

PERU

A caustic soda—chlorine plant is now on stream in Peru and will supply chemicals to industries in Latin American markets.

TUNISIA

Förenade Superfosfatfabriker de Hälsingborg (Sweden) has signed an agreement with the Tunisian Government for the construction of a wholly-owned 100,000 ton/yr superphosphate plant at the coastal town of Sfax. The Swedish company will, itself, raise the capital estimated at 35 million crowns and construction is expected to take 3-4 years.

YUGOSLAVIA

A $23 million loan, by the American Fund for Economic Development, has permitted the construction of a petrochemical plant at Fagreb. Equipment has already been ordered from the U.S.A. and G.B.

Raw material will be natural gas from the petroleum deposits of the Struzec region. Expected output is 15,000 tons of polyethylene and polystyrene per annum and 15,000 tons of other basic materials for the manufacture of Perlon, synthetic detergents and rubber.

Company News

Hercules Power Co., of Philadelphia, is forming a manufacturing subsidiary in Finland to produce chemicals for the Finnish paper industry.

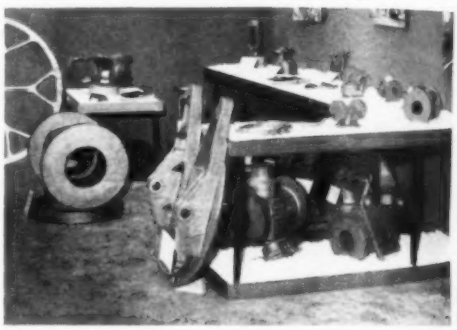
Flexibox NV—a new company—will be formed to handle sales of mechanical seals in the Benelux countries.

G. & J. Weir Holdings Ltd., who own 50 per cent of the issued share capital of Weir-Catton Ltd., are to acquire the remaining shares of that company. The firm manufactures quality castings in carbon, low alloy and stainless steels for a wide range of industrial applications.

J. A. Radley (Laboratories) Ltd. has been registered as a limited company and will continue to supply analytical, technological and developmental services as before.

F. J. Stokes Corp., of Philadelphia, has established a subsidiary company in Great Britain. The company, F. J. Stokes Ltd., will manufacture a wide range of machines and equipment for the plastics, chemical, pharmaceutical and associated industries.

Cast Steel Components for Industry



The North British Steel Foundry Ltd., of Bathgate, Scotland, have recently demonstrated how the quality and soundness of cast steel components are subject to controls at every stage. Particularly important in terms of the finished castings are methods engineering, pattern making, sand practice, melting, heat treatment and inspection procedures.

The capacity of this foundry is between 150 and 200 tons of finished steel castings per week. The weight range of the steel castings produced is from a few lb up to 10 tons.

Illustrated above are a selection of carbon and alloy steel castings of valves and fittings for a wide range of uses in the chemical industry.

New Processes

Aluminium from Clay

The production of aluminium from clay which is important to countries deficient in bauxite resources has been the subject of a number of research programmes carried out by U.S. companies. The Olin Mathieson Chemical Corp. and the Anaconda Co. being cases in point. Indeed, Anaconda have already produced aluminium from clay on a small pilot-plant scale, and Olin Mathieson recently announced the development through the pilot-plant stage of a process for purifying aluminium sulphate obtained by the acid treatment on clays and shales.

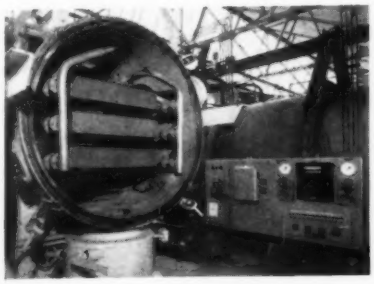
This development removes one of the major technical obstacles in the clay process, a significant advantage of which is that it offers a means of producing aluminium where cheap power is available without the need to compromise on plant location in order to suit both raw material and power sources.

New Plants

Freeze Drying of Foods

Mitchell Engineering Ltd. have just completed extensions to Britain's first large-scale industrial freeze-drying plant. Blood plasma, vaccines and biological materials have already been treated and preserved by this process, and now manufacturers of foodstuffs will be invited to freeze-dry their own products as an experiment.

The process consists of freezing the substance and removing its water vapour by sublimation under vacuum whilst the



substance remains as a frozen solid. The water vapour is removed from the system by means of a refrigerated vapour condenser or a steam ejector. The illustration shows the tray assembly at a pilot plant freeze-drying coffee. Evacuation of the cabinets to a pressure of 0.1 mm Hg is achieved by means of suitable high-vacuum pumps.

Alkylamine production at I.C.I.'s Billingham Works is to be increased. A completely new methylamine plant will be built with a capacity more than five times that of the existing unit. It is due for completion in 1963 and will be one of the largest in the world using the most advanced manufacturing techniques. Production capacity of the ethylamines will be more than doubled.

These expansions are to meet the growing demands at home and in the export market.

I.C.I. Billingham Division have developed a highly efficient process for making, at a lower cost, hydrogen which is the first stage in the manufacture of ammonia, fertilizers, and many of the other products of the Division. This process will use light oil as a raw material in place of the coke which is at present used. £6 million will be spent on modernizing a large section of the works during the next two years.

The new I.C.I. plant for manufacturing "Melinex" polyester film was opened at Dumfries recently. It has an annual capacity of 2,000 tons.

British expansion into the European Common Market is to be developed by I.C.I. Ltd., who are negotiating for a 300-acre site near Rotterdam. The company intends to build a large chemical plant manufacturing petroleum chemicals, including plastics and related products. Construction will begin early next year and £100 million may be spent in the next decade. The decision to establish a major chemical works in Rotterdam reflects the company's intention to pursue a vigorous drive for chemical business in Western Europe.

The first plants are not expected to come on stream before 1964.

The British Oxygen Co. Ltd. are building a third 200 tons a day oxygen plant for Richard Thomas & Baldwins Ltd. at their Newport steelworks. The new plant, operational by 1963, will bring the total daily capacity at Newport to 600 tons of high-purity oxygen.

Liquid hydrogen and liquid helium can now be produced at a new plant in service with The British Oxygen Co. Ltd., Scientific Division, Morden, Surrey.

Styrene production facilities of The Cosden Petroleum Corp. have been expanded, tripling the styrene monomer capacity to 70 million lb annually.

I.C.I. Ltd. announces that the capacity of its new polypropylene plant at Wilton, which came on stream at the end of last year, is to be doubled from 11,000 tons to 22,000 tons. Constructors John Brown Ltd., which built the plant, will be responsible for the extensions.

A fumaric acid plant with a capacity of 5 million lb a year is to be built at the Newport factory of Monsanto Chemicals Ltd. To be completed in 1962, it will be a logical supplement to the 15 million lb a year capacity of the maleic anhydride plant. Fumaric acid is principally used in the manufacture of polyester resins, resins for surface coatings and printing inks, plasticizers, fungicides, pharmaceuticals and textile finishes.

Monsanto Chemicals Ltd. announce that since commissioning their polyethylene plant at Fawley, its capacity has been increased from 10,000 tons to more than 17,000 tons per year. Production of this versatile plastic will be further expanded and new grades produced.

The Dunlop Rubber Co. Ltd. and Rubber Reclaiming Co. Inc., of Buffalo, are to build a rubber reclaiming plant near Liverpool. It will employ the Reclaimator process developed by the American company and is expected to be in production by mid-1962.

Problems Solved

Unusual Method of Carrying Oil

An unusual method of transporting oil is to be used by BP Australia for shipping lubricants to Tasmania from its Spotswood blending plant near Melbourne.

The lubricants are to be carried in specially-made rubber bags. These bags will be first placed empty into the standard steel crates used on the local cargo-carrying ships, and then filled.

After discharge, on the return journey it will be possible to pack six empty bags into one crate, thus freeing the remainder for shipping other commodities.

Impervious Graphite Units Replace Corroded Metallic Equipment

Alloy coils used for heating a mixture of phosphoric and hydrochloric acids in the presence of organic chemicals (used in the manufacture of pesticidal organic phosphorous compounds) proved to have but a short life.

By installing impervious graphite plate heaters in place of the metal units, the need for replacements were eliminated and the production cycle was reduced from nineteen to fourteen hours.

A further example of replacement of metallic heat exchange equipment by impervious graphite equipment for the sake of better corrosion resistance concerned a steel bundle in an all-steel shell and tube heat exchanger which had suffered serious corrosion on the tube side. 20 ft long tubes were used and there were two passes in the shell. An entire graphite tubing bundle was fitted inside the existing steel shell and has since given satisfactory service.

In both cases the equipment was made by the Carbon and Graphite Department of the Union Carbide International Corp.

Inconel Equipment for Coal Tar Processing

The presence of ammonium chloride in a coal tar fractionating plant led to rapid deterioration of a reflux condenser, the normal life of which was little more than a year. Another difficulty was that the 40-ft-high unit was enclosed in a structure which must be dismantled before the condenser can be removed.

Extended tests on a number of materials set up in corrosion spools and placed in position at corrosion sites showed that Inconel (79.5 Ni/13 Cr/6.5 Fe) offered the best prospect as a condenser material.

As a result, a new condenser with its tubes, tube sheets, baffles, baffle supports, expansion joint, gasket, and shell all made of Inconel was installed and has shown satisfactory resistance. In addition, Inconel bubble caps and trays were fitted in the upper 15 ft of the fractionating tower.

An Approach to Pollution Problems

An established and complex industrial plant for chemical manufacture has many old unsolved air pollution problems. Constant revision and the introduction of new

Continued on next page

processes or additions often add to these problems. A somewhat empirical approach has been developed which copies with the vent problem *in situ* and "pilot plants" the proposed air cleaning method without appreciable expenditure of capital or engineering time.

A lightweight fibreglass-reinforced 1 ft diameter scrubber tower made in short spool sections is used as a packed scrubber, spray tower, mist eliminator or combination unit as the problem dictates. The unit is operated at the vent site. Several examples of the applied use of the unit are given, including sulphuric acid mist elimination from sulphur burning process vents. Auxiliary sequential sampling equipment and analytical procedures are discussed.

Personalities

Mr. Charles Hull has been appointed General Manager of the Shell Refining Co. Ltd.'s Stanlow Refinery.

Obituary Notice—MR. R. B. KERR, M.B.E., died on February 22, 1961. He was Deputy Managing Director of Foster Wheeler Ltd., and was both an associate member of the Institute of Petroleum and a graduate of the Institute of Chemical Engineers.

Sir John Carmichael, K.B.E., has been appointed to the Board of Fisons Ltd.

Mr. C. F. Kearton, O.B.E., Managing Director of Courtaulds Ltd., and distinguished for his work on chemical engineering characteristics of volatile uranium products and for technological development in the textile industry, has been elected a fellow of the Royal Society.

Contracts

Petrocarbon Developments Ltd. is to supply an £800,000 polystyrene plant to Rumania. The suspension polymerization process developed in the U.K. will be employed. An essential feature of the plant is its extreme flexibility, which enables production to be changed rapidly from one grade to another.

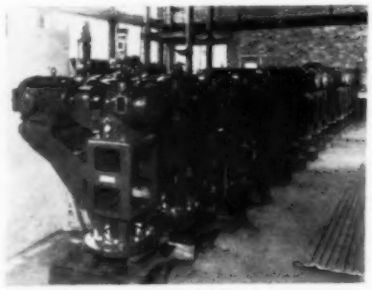
Chemical Construction (G.B.) Ltd. has received a contract to supply full process design and detailed engineering services relating to a sulphuric acid concentration plant of the submerged combustion type. It will be erected in Mexico and will produce 30 short tons per day.

Constructors John Brown Ltd. and Fisons Ltd. are to design and supply two major chemical plants for Techmashimport of Moscow. One plant is for the production of DMEU (dimethylol ethyleneurea) used in the manufacture of "drip-dry" fabric. The plant, which will be highly automated, can produce 12,000 tpa.

The other plant is to produce MCPA, a well-known hormone weed killer. The contracts are worth more than £2 million.

Strojexport, of Czechoslovakia, will supply the U.A.R. with a water treatment plant to be erected at Cairo.

Lightnin Mixers Ltd. report the recent despatch to Australia of 47 units from the standard Lightnin fluid mixer range.



Many of the units are fitted with mechanical seals. The mixers will be used in a new synthetic rubber plant.

On exhibition at The British Trade Fair in Moscow will be models of parts of the two fatty alcohol plants to be built in Russia by Marchon Products Ltd. This £3 million contract for a detergent chemicals plant will be completed in association with C.J.B.

Bennis Thermoflash Ltd. is to supply a self-contained sea-water distillation plant to the ruler of a Sheikhdom in the Arabian Gulf. The output of pure water will be 25,000 gpd.

Recent contracts awarded to William Boby & Co. include an £18,000 de-aeration plant for Monsanto Chemicals Ltd., North Wales; a £13,000 dealkalisation-base exchange plant for I.C.I.'s new heavy organic chemicals factory at Severnside; and an £8500 contract for dealkalisation-base exchange and deaeration plants for J. & E. Sturge Ltd., Birmingham.

The de Havilland Aircraft Co. Ltd. have received an order for pottermeter type turbine flowmeters, to be used in conjunction with local and remote direct-reading totalizers and rate of flow indicators on the Burmah Oil Co.'s crude oil pipeline system now under construction in North-east India.

£750,000 worth of machinery and plant are now being shipped to the U.S.S.R. by Sterling Moulding Materials Ltd. The equipment is for Russia's first factory for the production of polystyrene moulding powders.

Conferences

At the Fourth Symposium on Temperature recently concluded in Columbus, Ohio, no less than 228 papers were presented covering temperature measurements from absolute zero to 10 million °K. Almost every area of engineering and instrumentation was presented, including the automatic control of temperature in industrial processes.

Of papers with an interest to chemical engineers may be the following: "The Control Systems Approach to Process Design"; "Analytical Tools Required for Temperature Control" (L. LEFKOWITZ); "Considerations in the Design and Selections of an Electrical Control System" (E. T. DAVIS); "Considerations in Designing a Pneumatic Temperature Control System" (M. O. DUSTIN and N. COURTRIGHT); "A Review of Automatic Radiometric Pyrometry" (S. ACKERMAN); "Automatic Two-colour Pyrometer" (B. F. BONAKER); "Design of an Automatic Two-colour Pyrometer" (S. ACKERMAN); "Design and Performance Characteristics of an Automatic Brightness Pyrometer" (J. S. LORD).

Many aspects of thermometry were reviewed, and, in this connection, the following papers may be mentioned: "A Review of the Pneumatic-probe Thermometer", I (WARSHAWSKY and P. W. KUHNS); "Heat Transfer Devices for Determining the Temperature of Flowing Gases" (L. N. KRAUSE, GEORGE E. GLAWE and R. C. JOHNSON); "The Gas-viscosity Thermometer and its Potential Usefulness below 20°K" (HAROLD J. HOGE); "Improved Sonic Pyrometer" (R. T. TERBUSH).

Another important U.S. conference was the 139th National Meeting of the American Chemical Society held at St. Louis late last month. From this large meeting a number of papers were given of interest to chemical engineers, in particular in the symposium dealing with the less common separation methods employed in the petroleum industry. Thus a number of papers were devoted to processes of membrane permeation and thermal diffusion. Among the other symposia were those on experimental and theoretical advances in elementary gas reactions, and machine methods in documentation; the latter brought forth a proposal (KURT GINGOLD) for a translation pool which would act as a centralized clearing house, handle translations from all sources irrespective of language and any branches of science and technology. It is envisaged that such a centre could sponsor research in translation matters, serve as an intermediary for new translation projects, and avoid the present duplication of effort on the part of individuals and specialist services.

Erratum—page 290 (April Issue)

Batch Tar Acid Distillation Column

The first sentence should read "A tar acid distiller . . .". Also, the trays used in the distillation column were of the Glitsch Ballast type.